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ENVIRONMENTAL CONSIDERATIONS FOR OIL SHALE DEVELOPMENT

Nick Conkle, et al

Battelle Columbus Laboratories

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ENVIRONMENTAL CONSIDERATIONS FOR OIL SHALE DEVELOPMENT

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The report gives results of a preliminary literature survey of environmental considerations associated with the development of a shale oil industry in the U.S. The survey was not meant to be an exhaustive analysis of the environmental aspects of oil shale production. The study includes: oil shale deposits, mining and pretreatment processes, in-situ and ex-situ retorting, refuse disposal, and produce treatment and usage. The report provides an overview of the anticipated oil shale industry, including available resources and the likely technical and environmental problems to be encountered. It identifies specific technologies likely to be employed in the mining, oil extraction, and on-site upgrading processes. It also describes the development status of these technologies and their potential economic, resource, and environmental impacts upon the oil shale resource regions. The report notes research and development needs required to eliminate inadequacies in the data base necessary to evaluate potential environmental problems.

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Reviews	Refuse Disposal	Stationary Sources	05B
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Mining			08I
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by

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WASHINGTON, D.C. 20460

October 1974

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ABSTRACT

Results of a preliminary literature study of the environmental considerations in the development of an environmentally acceptable oil shale industry are presented. The following seven different areas are included in the study.

Oil Shale Deposits
Mining, Handling, and Pretreatment Processes
In-Situ Retorting
Ex-Situ Retorting
Retorted Shale Refuse Disposal
Other Environmental Considerations
Product Treatment and Usage

Research and development needs required to eliminate inadequacies in the data base necessary to evaluate potential environmental problems are noted.

The report provides an overview of the anticipated oil shale industry, including the magnitude of the resources available and the likely technical and environmental problems to be encountered. Specific technologies likely to be employed in the mining, oil extraction, and on-site upgrading processes are also identified. The status of development of these technologies and their potential economic, resource, and environmental impacts upon the oil shale resource regions and the nation as a whole are also described.

This report was submitted in fulfillment of Task 7 of Contract 68-02-1323 under the sponsorship of the Office of Research and Development, Environmental Protection Agency.

MANAGEMENT SUMMARY

This report is the result of a study initiated by the United States Environmental Protection Agency. The effort was modest (about 2 manmonths) and the report is not meant to be an exhaustive or in-depth analysis of the environmental aspects of oil-shale production. In the years ahead shale-oil is expected to contribute significantly to the US energy supply and will obviously be a growing industry. This report, then, is a preliminary study which can be a basis for further efforts to completely define the environmental problems and help develop an environmentally acceptable shale oil industry. Presented in Chapter IX is a summary of the research needs to achieve this goal.

Shale Oil Availability

The large quantity of oil-shale reserves and resources available is a positive component of US energy resources. Estimated reserves constitute the equivalent of 80 billion barrels of oil and can provide a good supply of the total oil consumption rate which is currently about 7 billion barrels per year. Resources the equivalent of 1,800 billion barrels are located in the Green River formation of several basin areas in Northwestern Colorado, Northern Utah, and Southwestern Wyoming. This formation ranges in thickness from a few hundred to about 2,100 meters, underlying an area of roughly 44,000 square kilometers(5). Although oil shale deposits are found in numerous areas of the United States, the Green River formation is at present the only deposit of adequate size and availability to have potential commercial value.

About 70 percent of the reserves and 78 percent of the resources are located on Federally owned lands. Therefore the extensive development of the largest amount of the nation's oil shale potential will be contingent upon the issuance of Federal leasing policies, plus the resolution of title questions on significant parts of the Federal lands. It is practically certain that the Federal government will act favorably on these matters if private companies decide to make the investment decisions required to start up a full-scale oil shale producing industry.

Other minerals associated with oil shale could be recovered as salable by-products resulting from retorting and refining operations. Two such minerals, dawsonite [$NaAl(OH)_2CO_3$] and nahcolite ($NaHCO_3$), could produce large quantities of alumina and soda ash, respectively.

Mining and In-Situ Oil Recovery

Two major options are under consideration in this phase of oil shale development: mining followed by surface processing of the oil shale (ex-situ), and in-situ (or in-place) processing of the oil shale. Of the two options, only the adit mining (horizontal entrance into a mine) and surface processing approach is believed to have been advanced to the point where it may be possible to scale up to commercial production during this decade. Until only recently, virtually all efforts to develop oil shale technology were directed toward conventional mining, crushing, and ex-situ retorting.

Oil shale mining by either underground or surface methods differs very little from conventional coal mining methods. Major advances in underground mining of oil shale were achieved by the Bureau of Mines in its Oil Shale Program during 1944-1956. The state of technology of underground mining of oil shale is highly developed. The same cannot be said for surface mining or in-situ methods of oil recovery, although surface mining methods seem quite feasible for certain shale deposits. In-situ methods have been studied and much experimentation has been undertaken by private companies. For the most part results of their work are not made public. Based upon current data it is believed that it would take about five more years to develop the in-situ method to a commercial stage.

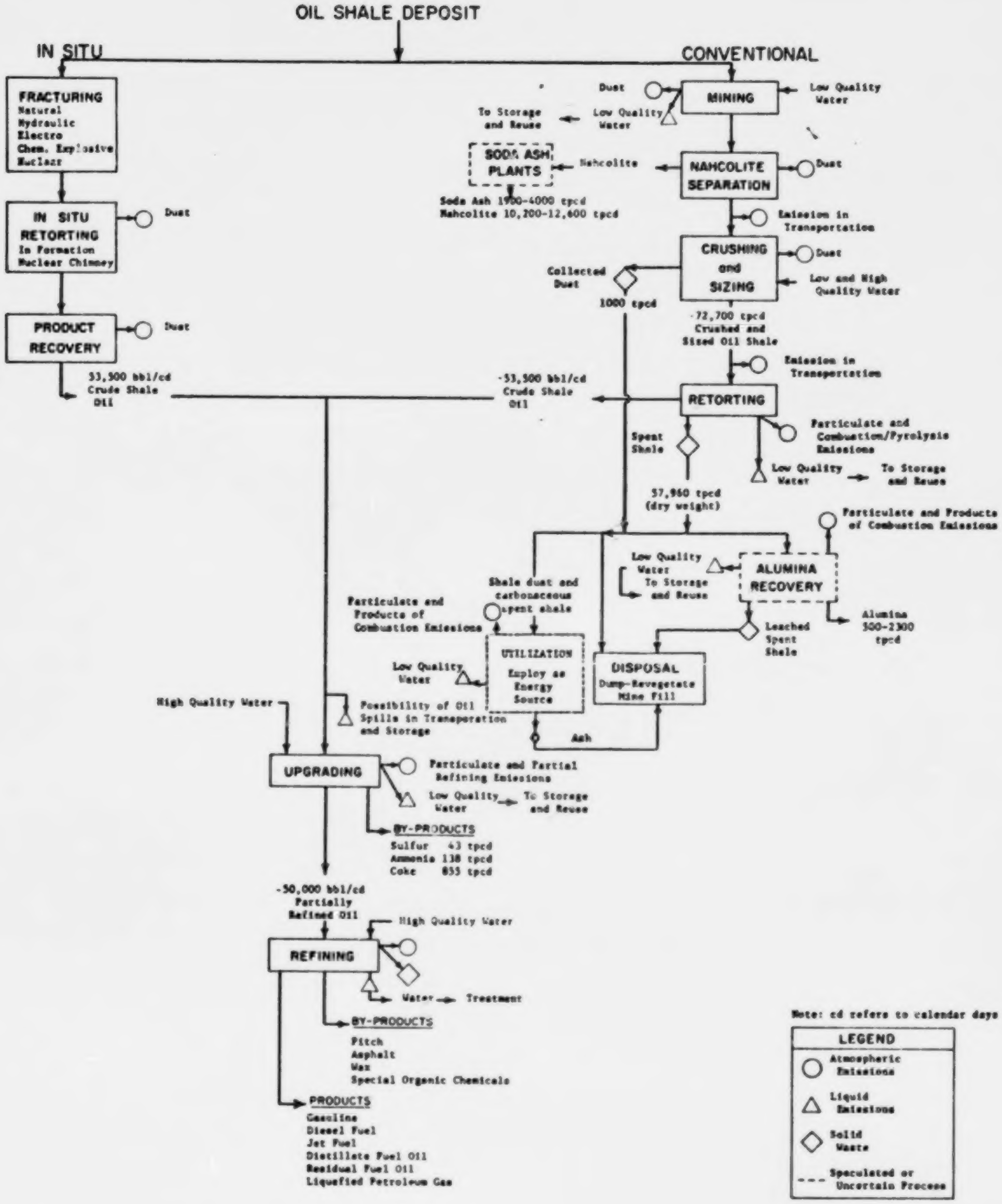
Environmental problems resulting from underground mining and in-situ methods of recovery seem controllable. However, there would be serious environmental problems if nuclear devices were to be used for underground fracturing of shale preparatory to underground retorting. These problems would involve surface subsidence, effect on air and underground water, safety, and possible radioactivity of the retorted oil brought to the surface. Surface mining methods such as open pit mining or strip mining, could have an adverse impact. Effects on soils, vegetation, topography, specific land and cultural features, water quality, air quality, wildlife habitat, grazing patterns, and recreation would have to be controlled. Overburden removed for strip mining would have to be replaced into mined-out areas and revegetated. Open pit mining's environmental impacts would be essentially the same as for strip mining. When an open pit mined area was exhausted of shale, spent shale from retorting could be used to fill the pit followed by soil cover sufficiently to permit revegetation. The figure on page vii presents the environmental emissions identified in this study which are associated with exploitation of oil shale deposits by either conventional or in-situ techniques.

Ore Handling and Pretreatment

Oil-shale ore handling and pretreatment prior to retorting present, by and large, little difficulty in an overall oil shale-producing complex.

Environmental impacts from ore dressing for an underground mine are minimal when performed within the underground operations. For surface ore dressing, environmental impacts are significant and are intimately associated with other surface operations. Dust generation from crushing and allied operations and from the transportation of ore to crushing facilities would, according to one estimate, result in overall dust losses of about 1.3 percent of the shale ore handled(5). This estimate was based on experience of 15 to 20 years ago by the U.S. Bureau of Mines. Today there are equipment and methods that could significantly reduce the loss of airborne particles to the atmosphere. The effect of the product loss on product cost is difficult to estimate from available data.

Process flow stream dust losses can be collected with conventional collection equipment, dampened, and disposed of with the spent shale residue from the retorting plants.


OIL SHALE DEPOSIT
IN SITU
CONVENTIONAL
FRACTURING
Natural
Hydraulic
Electro
Chem. Explosive
Nuclear
IN SITU RETORTING
In Formation
Nuclear Chimney
Dust
PRODUCT RECOVERY
Dust
53,500 bbl/cd Crude Shale Oil
Dust
MINING
Low Quality Water
Low Quality Water
To Storage and Reuse
SODA ASH PLANTS
Nahcolite
NAHCOLITE SEPARATION
Dust
Soda Ash 1900-4000 tpcd
Nahcolite 10,200-12,600 tpcd
Emission in Transportation
CRUSHING and SIZING
Dust
Low and High Quality Water
Collected Dust
1000 tpcd
~72,700 tpcd Crushed and Sized Oil Shale
Emission in Transportation
RETORTING
~53,500 bbl/cd Crude Shale Oil
Spent Shale
Particulate and Combustion/Pyrolysis Emissions
Low Quality Water
To Storage and Reuse
57,960 tpcd (dry weight)
Particulate and Products of Combustion Emissions
Low Quality Water
To Storage and Reuse
ALUMINA RECOVERY
Alumina 500-2300 tpcd
Leached Spent Shale
Shale dust and carbonaceous spent shale
Particulate and Products of Combustion Emissions
UTILIZATION
Employ as Energy Source
Low Quality Water
DISPOSAL
Dump-Revegetate
Mine Fill
Ash
High Quality Water
Possibility of Oil Spills in Transportation and Storage
UPGRADING
Particulate and Partial Refining Emissions
Low Quality Water
To Storage and Reuse
BY-PRODUCTS
Sulfur 43 tpcd
Ammonia 138 tpcd
Coke 855 tpcd
~50,000 bbl/cd Partially Refined Oil
High Quality Water
REFINING
Water
Treatment
BY-PRODUCTS
Pitch
Asphalt
Wax
Special Organic Chemicals
PRODUCTS
Gasoline
Diesel Fuel
Jet Fuel
Distillate Fuel Oil
Residual Fuel Oil
Liquefied Petroleum Gas
Note: cd refers to calendar days
LEGEND
○ Atmospheric Emissions
△ Liquid Emissions
◇ Solid Waste
--- Speculated or Uncertain Process

SCHEMATIC FLOW OF OIL SHALE RECOVERY AND ASSOCIATED EMISSIONS

Retorting

The retorting process considered most promising on the basis of ease of environmental effluent control, shale oil extraction efficiency, and technical advancement is the Oil Shale Corporation's TOSCO II retort. This system, involving a horizontal rotary kiln heated by externally fired ceramic balls, has several specific advantages: (1) low, controlled temperature retorting allowing a minimum of carbonate decomposition, (2) production of undiluted, high Btu retort gas - possible because the heat required for retorting is generated (by combustion) external to the retort, (3) extremely high shale oil extraction - possible because of the systems' capability to utilize finely crushed shale, (4) the production of an additional fuel source in the form of carbonaceous residue remaining on the spent shale, and (5) many years of active investigation, optimization, and refinement of the retorting process culminating in the successful, continuous operation of the largest capacity oil shale retort in the U.S.

A possible variation in the use of TOSCO retorts showing promise would be the combined use of both TOSCO retorts and some vertical shaft retort, e.g., Gas Combustion, Union Oil, or Petrosix retorts. Such a combination would allow an improved efficiency in the crushing and screening operations. This is done by using the larger pieces of shale for the vertical shaft retorts and the fines for the TOSCO retort, thus reducing both the quantity of fines generated and the required degree of crushing. In addition to the economic advantages (from reduced equipment requirements and energy and water usage) the possibility of air and land pollution would be lowered. Another possible advantage from a combined operation would be the use of low Btu retort gas from an internal combustion heated vertical retort (Gas Combustion or Union Oil retorts) to provide fuel to heat the ceramic balls for the TOSCO retort. Such an operation could free the high Btu retort gas from the TOSCO retort, which, because of its high sulfur concentration,can be economically desulfurized and used as a high quality, clean burning on-site fuel gas or exported.

Potential environmental problems resulting from the oil shale retorting operation include atmospheric emissions of particulates, oxides of sulfur and nitrogen, hydrocarbons, and carbon monoxide. Presently, data to accurately estimate the quantities of these pollutants are lacking. However, inspection of the retorting process control mechanisms indicates that the major environmental problem area will not be in the control of the retorting operation itself but in the upgrading and utilization of the products of the retorting operation.

Particulate levels in the product gas stream are expected to be low because they are removed simultaneously in the oil removal operation. However, the hydrogen sulfide content in the gas is high and when combusted is expected to result in unacceptable emission levels of sulfur oxides unless some form of stack gas desulfurization or pre-combustion treatment for removal of the sulfur from the gas is undertaken.

Significant quantities of nitrogen oxides could also be emitted from the combustion process.

Upgrading crude shale oil is another potential environmental problem area. The oil must be upgraded to a pumpable quality and sulfur and nitrogen levels must be reduced. The anticipated method for this upgrading operation is delayed coking and catalytic hydrogenation. Data necessary to accurately assess the magnitude of the anticipated emissions from these upgrading operations are presently lacking. Emissions of particulates, sulfur, hydrocarbons, and carbon monoxide are likely. While these operations can be similar to those currently employed in petroleum refineries, data are lacking on actual upgrading of shale oil necessary to determine environmental problem areas. It is emphasized at the risk of repetition that the lack of data is a serious hindrance to the quantification of pollutants; consequently, defining the extent of environmental problems of this potentially vast industry is not easily accomplished.

Refuse Disposal

The refuse disposal scheme most promising on the basis of developed technology, economics, and environmental protection is the transport of the cooled and moistened refuse in a system involving minimum handling, such as truck or covered belt transport, to adjacent canyons or other topographic depressions where it would be landfilled. Potential water pollution from runoff from the disposal areas can be safeguarded by dams, culverts, retaining ponds, and/or diversion ditches. Erosion of the residue piles will be avoided by stabilization techniques including special placement of the waste in thin layers maintaining a low angle of repose to insure frictional stability. Chemical stabilization may also be used, and eventually vegetative stabilization through import of soil and fertilization prior to seeding to produce native vegetation can be employed.

Utilization of underground mined out areas as a disposal location in the distant future appears likely but not until a significant fraction of the mine's ore has been extracted. Both belt and slurry transportation methods are considered feasible, however the lack of adequate supplies of water along with certain technical problems of settling, particle size, etc., may preclude the use of slurry systems on an extended scale.

Utilization of the spent shale as a source of valuable raw materials would be the most favorable method of refuse "disposal". However, it is not likely in the near future. Several obstacles lie in the path to large scale extraction of the aluminum and sodium based minerals from the spent shale. Not the least of these is the lack of a proven and tested extraction technology. Possibly as significant are the market uncertainties and the bleak forecasts of limited future markets for the vast quantities of these minerals. Even alumina may experience difficulties entering into the tough international bauxite market. Capital investments for alumina extraction processes and associated pollution control facilities would be many millions of dollars. There is also the uncertainty regarding long term availability of alumina ore from this source.

Product Usage

Products from the retorting of oil shale and the necessary on-site upgrading operations will represent new fuel and chemical supplies. Basically, three main groups of products will be derived: gaseous fuels, liquid fuels, and solids. Retort gas and gases created in the cracking of the shale oil in the hydrogenation operations will primarily serve in-house fuel needs. These gases, whether desulfurized before or after combustion, are envisioned to be utilized for electricity and steam generation and as fuel gas in on-site upgrading processes. Because the entire quantity is anticipated to be consumed on site, this product's effect on the nations' total energy requirements should be negligible.

The liquid product from retorting is generally a viscous, foul smelling, waxy, high-nitrogen, high-sulfur oil. Direct combustion of this crude shale oil is not envisioned. Instead, upgrading to pumpable quality followed by transport to a petroleum refinery for processing is the more likely route. The upgrading process involving delayed coking and catalytic hydrogenation produces a desulfurized, denitrified, synthetic crude oil, plus additional fuel gas and sulfur, ammonia, and green coke as by products. Although this syncrude has some unusual characteristics compared to petroleum crude it is expected to be readily acceptable to processing by conventional techniques. The main products will be gasoline, jet and diesel fuel, and domestic and industrial heating oils. A variety of refinery by-products similar to those obtained from petroleum crude oil refining, plus a number of more unusual products are anticipated. The main products and most of the by-products from syncrude refining are expected to supplement current industry fuel and chemical supplies.

The energy needs of the nation will be supplemented by the fuel products derived from oil shale. However, the significance of shale oil will naturally depend on the extent of development of the oil shale industry. Various predictions on the rate and level of anticipated development abound, ranging from 100,000 to 1 million (MM) bbl/day capacity by 1985. Probably, the National Petroleum Council's estimate of a maximum capacity of 400,000 bbl/day by 1985 is reasonable. The quantity of oil estimated to be required for domestic use by 1985 is 26 MM bbl/day of which 57 percent is anticipated to be foreign oil. Development of the oil shale industry to the 400,000 bbl/day level would provide just about 2 percent of this requirement, and, reduce foreign oil requirements by just 3 percent. Because of the limitations of manpower, equipment, and logistics, the growth of shale oil production capacity will be limited to 400,000 bbl/day by 1985 with simultaneous construction resulting in an annual increase in capacity of only 100,000 bbl/day. While such growth is not anticipated to keep pace with America's energy needs, it should provide a significant new source of liquid fuels and chemicals.

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PRELIMINARY LITERATURE STUDY OF ENVIRONMENTAL CONSIDERATIONS FOR OIL SHALE DEVELOPMENT

I. INTRODUCTION

Large land areas of the United States are known to contain oil-shale deposits, but those areas in Colorado, Utah, and Wyoming that contain the shale-rich sedimentary rocks of the Green River Formation offer the greatest promise for shale oil production in the future. These oil shales occur beneath 64,750 square kilometers (25,000 square miles) of land area, and of this area 44,030 square kilometers (17,000 square miles) are believed to contain oil shale of potential value for commercial development in the foreseeable future.(5)

The known Green River Formation deposits include high-grade shales, in beds at least 100 meters thick and yielding 104 liters per kkg* (25 or more gallons per short ton) of oil containing about 600 billion barrels** of oil.(5) Recovery of even 10 percent of this resource would represent a significant energy source adequate to supplement the Nation's oil supply for two to three decades, providing economic and environmentally safe methods of shale oil production are developed.

The Synthetic Liquid Fuels Act of April 5, 1944, as amended, made possible a large-scale oil shale research and demonstration effort by the United States Department of the Interior (USDI) Bureau of Mines during the period 1944-56. This effort was aimed at the creation of new and more economical mining, retorting, and refining technologies, and also sought to provide reliable information on the costs of commercial shale-oil production. Industry has also conducted extensive research on oil-shale processing.

Commercial shale-oil production, under USDI's most optimistic estimate, could begin about 1975 at a rate of about 18 million barrels per year (50,000 barrels per day). The first generation technology available for the initial commercial production would be improved from 1976 to 1980. This developmental stage will experience incremental annual production increases of about 18 million barrels every year as the new technologies are applied so that by 1980, a cumulative productive capacity of more than 100 million barrels per year could be established. More importantly, the technology probably will have been advanced to the point where larger incremental increases in production could be achieved. The nucleus consisting of people, supporting services, facilities, and experience needed for this expanded effort will have been established. After 1980, the second generation extraction-retorting systems would be expected to permit annual additions to shale-oil productive capacity of about 37 to 73 million barrels per year (100,000 to 200,000 barrels per day).

---

* kkg - kilo kilograms or 1000 kilograms.

** This represents about 300 percent of all known and probable liquid fuels reserves of the United States.

In-situ retorting is still in the process of development. However, by 1985, cumulative capacity, both in-situ and ex-situ, is estimated between 400,000 and 1 million barrels per day, the latter being the most optimistic prediction from both private and public lands.

Such an oil-shale development would produce both direct and indirect changes in the environment of the oil-shale region in each of the three states where commercial quantities of oil-shale resources exist. Many of the environmental changes would be of local significance. Others (e.g., air emissions) would be of an intra- and interregional character and have a cumulative impact. Impacts would include those on water quality, air quality, ecosystems, habitats, grazing and agricultural activities, recreation and aesthetic values, and on the existing social and economic patterns.

II. OIL SHALE DEPOSITS

Location, Classification, and Ownership

Although oil-shale deposits are found in numerous areas of the United States, the only deposit of adequate size with potential commercial value at the present time is the Green River Formation shown in Figure 1. This formation ranges in thickness from a few hundred to about 2,135 meters (7,000 feet), underlying 44,030 square kilometers (17,000 square miles) of several Northwestern basin areas in Colorado, Northern Utah, and Southwestern Wyoming. Location of thick deposits, mainly dolomitic shales and marlstones, is shown in the figure. In general, the central parts of the Piceance Basin in Colorado and the Uinta Basin in Utah contain thick, rich oil shale sequences which grade to thinner and leaner oil shale at the basin margins. Somewhat thinner and generally lower-grade deposits in the Green River and Washakie Basins of Wyoming also show decreases in grade toward the basin margins.

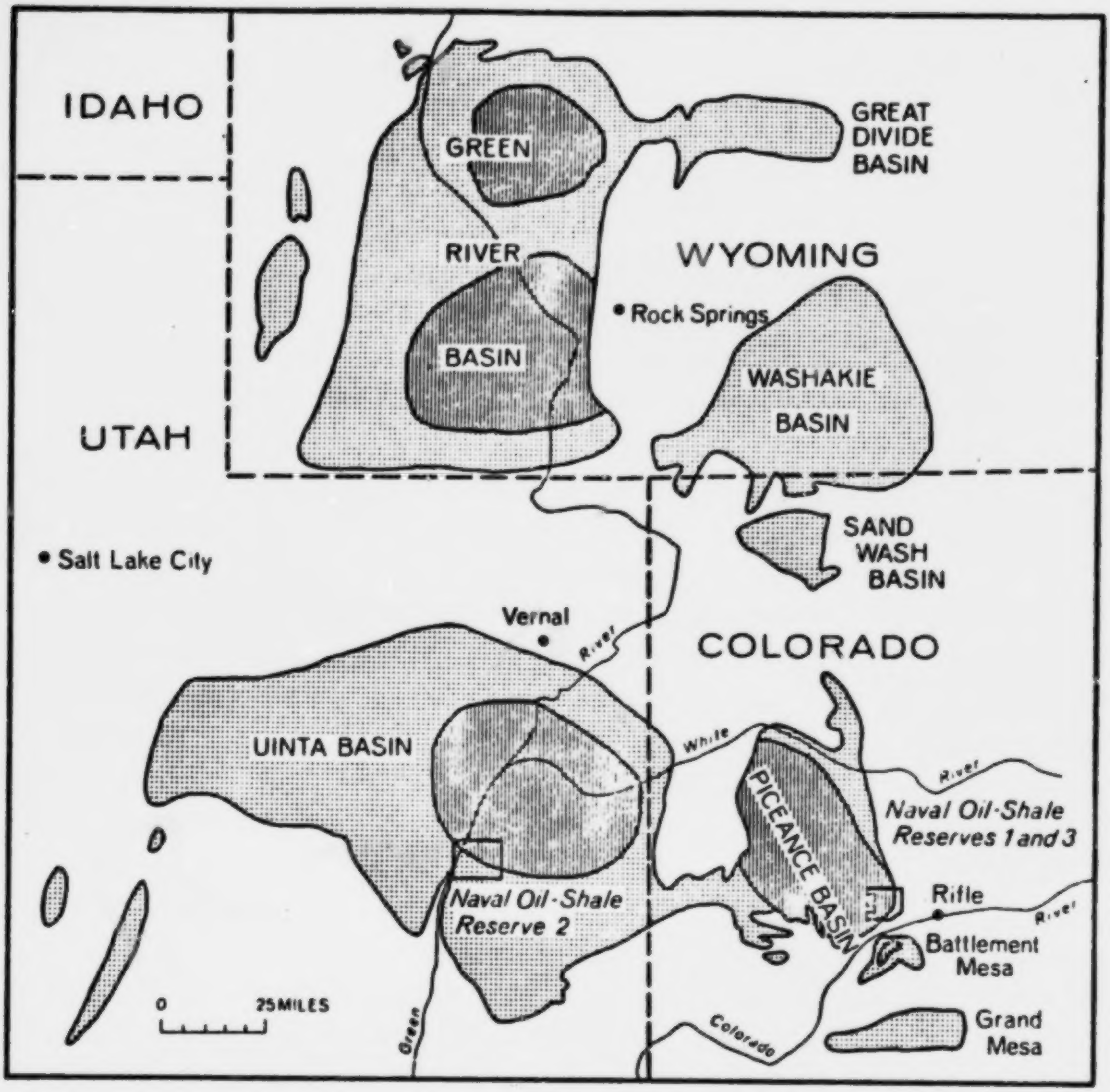
The National Petroleum Council's "Other Energy Resources Subcommittee" has made estimates of energy availability from oil shale. In their initial appraisal they surveyed the existing work and literature on oil shale resources and interpreted these in light of the reserves which may be recoverable at varying degrees of commercial attractiveness.

Basic assumptions underlying the NPC estimates were:(1)

(a) Only the Green River Formation shales were commercially attractive.

(b) Reserves will average 60 percent of the in-place resources and will be recoverable mainly by underground mining.

(c) Early interest will center on zones of shale at least 10 meters (30 feet) thick and yielding at least 125 liters per kkg (30 gal/ton) of shale oil.


IDAHO
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RIVER
BASIN
GREAT DIVIDE BASIN
WYOMING
Rock Springs
WASHAKIE BASIN
UTAH
SAND WASH BASIN
Salt Lake City
Vernal
River
COLORADO
UINTA BASIN
White
River
PICEANCE BASIN
Naval Oil-Shale Reserves 1 and 3
Naval Oil-Shale Reserve 2
Rifle
River
Battlement Mesa
0
25 MILES
Green
Colorado
Grand Mesa

EXPLANATION

░ Area underlain by the Green River Formation in which the oil shale is unappraised or low grade

▓ Area underlain by oil shale more than 10 feet thick, which yields 25 gallons or more oil per ton of shale

FIGURE 1. DISTRIBUTION OF OIL SHALE IN THE GREEN RIVER FORMATION: COLORADO, UTAH, AND WYOMING (1)

Classification of Oil Shale Deposits(1)

In-place oil shale resources can be arranged in four classes each reflecting the degree of commercial attractiveness. These will be described below.

> Classes 1 and 2. In total, these are the resources satisfying the basic assumption that early interest will be limited to deposits at least 10 meters (30 feet) thick and averaging 125 liters per kkg (30 gal/ton) of shale oil. Only the most accessible and best defined deposits are included. Class 1 is a more restrictive cut of these reserves and indicates that portion which would average 146 liters per/kkg (35 gal/ton) over a continuous interval of at least 10 meters (30 feet).
>
> Class 3. These are resources which, although matching Classes 1 and 2 in richness, are more poorly defined and not as favorably located. They may be considered potential resources and would be exploitation targets at the exhaustion of Class 1 and Class 2 resources.
>
> Class 4. These resources are lower grade, poorly defined deposits ranging down to 63 liters per kkg (15 gallons per short ton) which, although not of current commercial interest, represent a target when their recovery becomes feasible. These may also be considered speculative resources.

The Mahogany zone in the Piceance Basin allows distinction between Class 1 and Class 2 resources.* There the resources averaging 146 liters per kkg (35 gal/ton) over a minimum 10-meter (30-foot) section were determined from available assay data from Mahogany core tests. Class 1 resources are estimated at 34 billion barrels. The remaining estimated 83 billion barrel Mahogany resources are designated Class 2, and contain an average of 125 liters per kkg (30 gal/short ton) and have the same minimum section thickness. The Uinta Basin has been estimated to contain 12 billion barrels of Class 2 resources.

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* Resources are oil shale deposits that are potentially recoverable. Reserves are the resources available for processing after mining and as assayed by the Modified Fischer Assay Method (Report of Investigations No 4477, June, 1949, USBM, Washington, D.C.).

Assuming that essentially all of the mineable resources will be recovered by underground mining, it can be estimated that an average of 60 percent of the resources are recoverable reserves after making an allowance for pillars, barriers between mines, and unforeseen contingencies. Reserves are known for Class 1 through Class 3 resources only. Class 4 resources appear mainly speculative at this time, and do not merit consideration as reserves before perhaps the year 2000. Estimated resources and reserves (at 60 percent recovery) are summarized in Table 1.(1)

As of 1972, only about 10 percent of the total oil shale resources shown in Table 1 were classified as reserves and about 10 percent of these were then considered reasonably prospective before 1985. This is probably a slightly pessimistic view considering the energy supply situation at present.

Ownership

An estimate of the ownership division of the Class 1 and Class 2 reserves is provided as follows:(1)

	Reserves at 60% Recovery (Billions of Barrels)	
Ownership	Class 1 Only	Class 1 + Class 2
Private Lands	6	17
Federal Lands - Clear Title	7	37
Federal Lands - Clouded Title*	5	20
Federal Lands - Naval Reserve	2	3
Total	20	77

---

* Federal lands with clouded title reflect only pre-1920 unpatented claims.

TABLE 1. SUMMARY OF OIL SHALE RESOURCES AND RESERVES AS OF 1971 GREEN RIVER FORMATION - COLORADO, UTAH AND WYOMING(1)
(Billions of Barrels)

Location	Resources					Reserves @ 60% Recovery			
	Class 1	Class 2	Class 3	Class 4	Total	Class 1	Class 2	Class 3	Total
Piceance Basin									
Colorado	34	83	167	916	1,200	20	50	100	170
Uinta Basin									
Colorado & Utah	--	12	15	294	321	--	7	9	16
Wyoming	--	--	4	256	260	--	--	2	2
TOTAL	34	95	186	1,466	1,781	20	57	111	188

It can be seen that 70 percent of Class 1 reserves and 78 percent of Class 1 plus Class 2 reserves are owned by the Federal Government. Thus, the main segments of reserves are located on Federally owned lands. Therefore, extensive development of the largest amount of the Nation's oil shale reserve awaits the further issuance of Federal leasing policies plus the resolution of title questions on significant parts of the Federal lands.

Of the 20 billion barrels in the Class 1 reserve category, a considerable fraction situated on private lands is available for development. Of these private lands, a substantial portion need land exchanges with adjacent Federal holdings to improve workable developments.

Quality of Shale Oil

The quality of shale oil recovered from the Mahogany zone of the Green River Formations by ex-situ processes typically ranges as follows: 19 to 28 degrees API gravity, high pour point (75 to 90 F), high viscosity (300 Saybolt Universal Seconds at 100 F), 0.75 percent sulfur, and about 2.0 percent nitrogen.(2) Shale oil produced by in-situ retorting has a higher API gravity, a lower pour point (9 F), a lower viscosity (41 SUS @ 100 F) and approximately the same sulfur and nitrogen levels. Shale oil is unlike crude oil in that it contains relatively larger quantities of nitrogen and oxygen compounds and unsaturates. The subject of shale oil quality will be discussed in more detail in later chapters of this report. It is expected that existing petroleum refineries can handle crude shale oil without major modifications to the refineries.

Associated Minerals

Oil shale consists of largely insoluble solid organic materials intimately associated with a mixture of minerals including alumina (Al_2O_3). Potential by-products are considered as minor or incidental salable products resulting from retorting and refining operations and are discussed later in this report. There is a good possibility of coproducing alumina and soda ash in addition to shale oil from the dawsonite- and nahcolite-bearing oil shale deposits in the north central part of Colorado's Piceance Creek Basin. Dawsonite [$NaAl(OH)_2CO_3$] intermingled with oil shale occurs over an area of 775 square kilometers (300 square miles) in a stratigraphic section of relatively rich oil shale below the Mahogany zone. The alumina content in these dawsonite shale beds is low compared to that of bauxite. However, if satisfactory alumina extraction methods were developed, the total quantity could be probably more than double the free world's known supply of alumina. Nahcolite, a naturally occurring sodium bicarbonate ($NaHCO_3$), is more abundant and more widespread than dawsonite in the Piceance Creek Basin.(3) Depending on production economics, soda ash could be produced from nahcolite occurring in these shales either alone or in combination with alumina. However, the future market for soda ash may not be large enough to accommodate such large-scale production.

There is great need for research, development, and economic studies to fully assess the importance of the large mineral deposits associated with oil shale and environmental studies of the impact of recovery.

Composition of Deposits

Data on mineral composition of bed samples from the Mahogany zone, Rifle, Colorado, are reported below. The ash content of raw shale varied from 59 to 70 percent by weight. The analysis for one of the ash samples showed: 46 percent silica (SiO_2), 4.36 percent ferric oxide (Fe_2O_3), 13 percent alumina (Al_2O_3), and 3 percent sodium oxide (Na_2O), with the remainder being magnesium oxide (MgO), potassium oxide (K_2O), and calcium oxide (CaO).

Spectrographic and chemical analyses(4) have indicated the presence of trace amounts (about 0.005 percent of each) of arsenic, boron, barium, chromium, copper, gold, silver, strontium, tellenium, titanium, vanadium, and zinc. It is necessary to investigate whether these will enter the atmosphere or waterways during processing, and if they do, whether they are sufficient in quantity to cause environmental damage.

Requirements and Incentives

Requirements for the exploitation of shale oil are listed as follows:

(a) Environmental protection measures that would be satisfactory to Federal, state, and local agencies but not so stringent as to discourage interest by private industry.

(b) Sufficient water supply over the long run so that the shale oil industry could expand into an extremely large operation up through the year 2000 and beyond.

(c) Manpower availability for construction of facilities and continued operation of an industry.

(d) Sound urban construction program to house and support the new employment which would result from oil shale development and would have to go forward probably concurrently with the construction of plants.

(e) The improvement of state and county roads and in some cases construction of new roads to handle an increased volume and weight of traffic resulting from increased industrial activity.

(f) The establishment of increased transportation access to oil shale areas by the two railroads (the Rio Grande Railroad and the Union Pacific Railroad) which now serve the oil shale areas.

(g) A need for extra pipelines for movement of shale oil from mining sites to refining centers. Some shale oil may move west to Salt Lake City and/or Los Angeles; however, it is likely that a good quantity of the oil will move east to Chicago and other midwestern refining centers. Existing pipelines would not have the capacity to handle their regular loads of oil and enlargements would have to be brought into service to handle the increased quantities of oil.

Incentives for the exploitation of shale oil can be listed as follows:

(a) In the face of the present national energy shortage, both short- and long-term, and the consequent rises in the price of energy, oil shale development appears more attractive day by day. Estimated oil shale deposits (equivalent to 600 billion barrels) can provide nearly 100 years supply of all liquid fuel needs of the U.S.

(b) Development of a Federal oil shale leasing program stimulating development of oil shale operations.

(c) Present technology, some recently developed, should make oil-shale mining and oil recovery economically feasible. Also, if shale-oil recovery begins, technological improvements would most certainly come about.

(d) The development of an oil-shale industry will eventually help the nation to become less dependent on imported sources of fuel.

III. MINING, HANDLING, AND PRETREATING PROCESSES

Two major oil-shale recovery options are under consideration for development: (1) underground mining (by adit or horizontal entry) followed by surface processing (ex-situ retorting) of the oil shale and (2) in-situ (or in place) processing. Of the two options, only the surface mining approach is believed to be advanced enough to enable scale up to commercial production by 1980. The relative state of knowledge of the various operations involved in oil-shale processing is shown in Figure 2.(5) The refining operations shown in Figure 2 would be performed outside of the oil-shale region at refinery centers located near markets for the final products. It is apparent from Figure 2 that various technical options are available for each phase of the operations.

There also is a third option, viz., surface mining - surface processing. Surface mining, similar to strip mining of coal, has serious disadvantages. Also, not many of the oil-shale tracts are amenable to surface mining. Hence, at the present time, this oil shale extraction method is receiving less attention.

Until recent years, virtually all efforts to develop oil-shale technology were directed toward conventional mining, crushing, and ex-situ retorting. Oil-shale processing in this manner requires considerable materials handling activities. Recently in-situ processing has been receiving attention and will be discussed in the next chapter.

Process Description

Mining

Neither surface nor underground oil shale mining methods differ greatly from conventional coal mining methods. Surface mining, usually termed open-pit or strip mining, requires removal and disposal of whatever overburden is present, followed by mining of the underlying oil shale in a quarry-like operation.

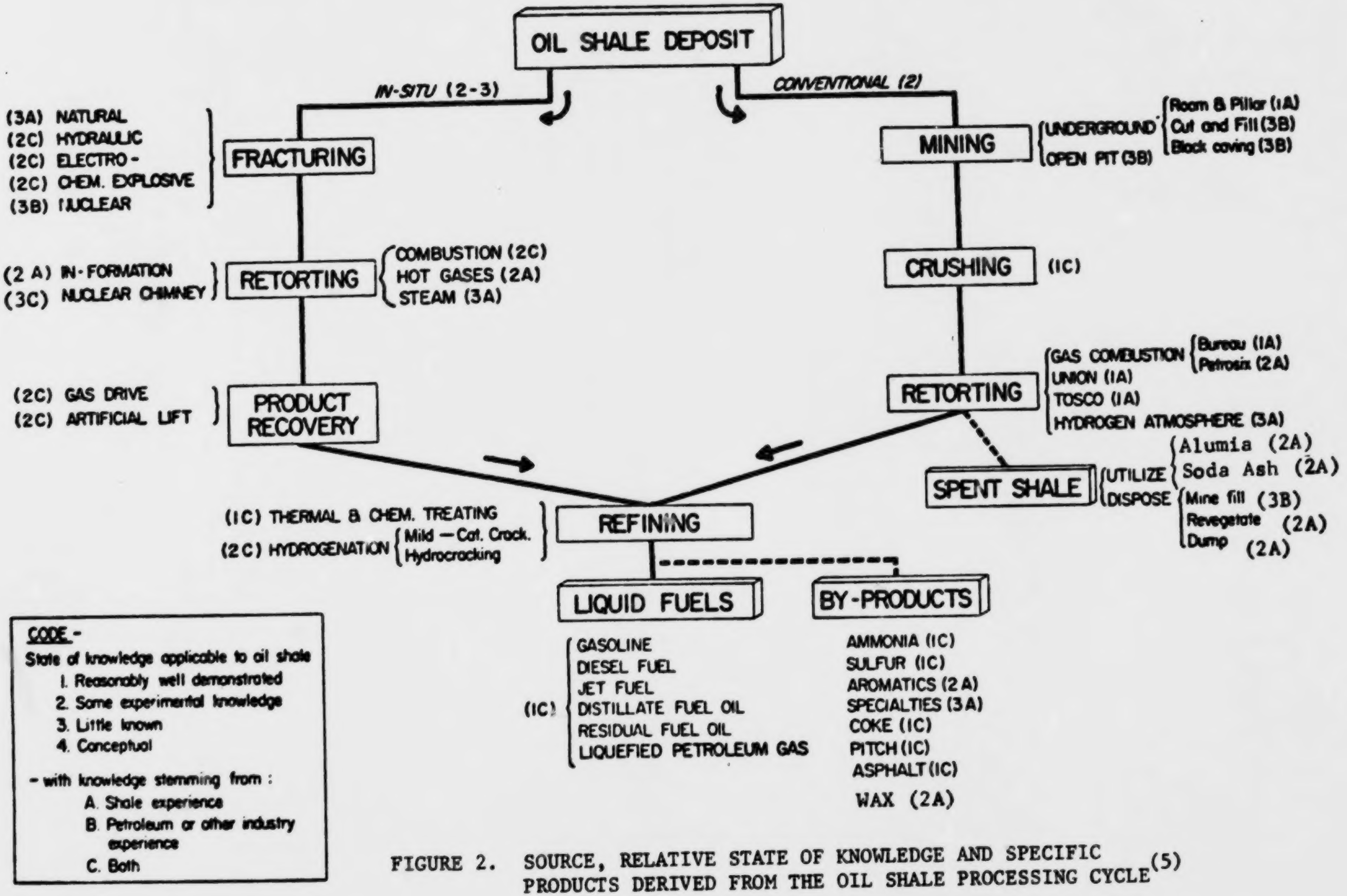
OIL SHALE DEPOSIT
IN-SITU (2-3)
CONVENTIONAL (2)
(3A) NATURAL
(2C) HYDRAULIC
(2C) ELECTRO-
(2C) CHEM. EXPLOSIVE
(3B) NUCLEAR
FRACTURING
(2 A) IN-FORMATION
(3C) NUCLEAR CHIMNEY
RETORTING
COMBUSTION (2C)
HOT GASES (2A)
STEAM (3A)
(2C) GAS DRIVE
(2C) ARTIFICIAL LIFT
PRODUCT RECOVERY
MINING
UNDERGROUND
Room & Pillar (1A)
Cut and Fill (3B)
Block caving (3B)
OPEN PIT (3B)
CRUSHING
(1C)
RETORTING
GAS COMBUSTION
Bureau (1A)
Petrosix (2A)
UNION (1A)
TOSCO (1A)
HYDROGEN ATMOSPHERE (3A)
SPENT SHALE
UTILIZE
Alumia (2A)
Soda Ash (2A)
DISPOSE
Mine fill (3B)
Revegetate (2A)
Dump (2A)
(1C) THERMAL & CHEM. TREATING
(2C) HYDROGENATION
Mild — Cat. Crack.
Hydrocracking
REFINING
LIQUID FUELS
BY-PRODUCTS
(1C)
GASOLINE
DIESEL FUEL
JET FUEL
DISTILLATE FUEL OIL
RESIDUAL FUEL OIL
LIQUEFIED PETROLEUM GAS
AMMONIA (1C)
SULFUR (1C)
AROMATICS (2A)
SPECIALTIES (3A)
COKE (1C)
PITCH (1C)
ASPHALT (1C)
WAX (2A)
CODE -
State of knowledge applicable to oil shale
1. Reasonably well demonstrated
2. Some experimental knowledge
3. Little known
4. Conceptual
- with knowledge stemming from:
A. Shale experience
B. Petroleum or other industry experience
C. Both

FIGURE 2. SOURCE, RELATIVE STATE OF KNOWLEDGE AND SPECIFIC PRODUCTS DERIVED FROM THE OIL SHALE PROCESSING CYCLE(5)

The greatest amount of actual experience in mining oil shale has involved underground mining techniques. Major advances in underground mining of oil shale were achieved by the Bureau of Mines in its oil-shale program during 1944-1956. The state of technology as reviewed by the Bureau of Mines in 1970 is quoted as follows:(2,6)

> "An underground mining method for oil shale was developed and demonstrated by the Bureau of Mines at its oil shale facility near Rifle, Colo., during 1944-56. A "demonstration mine," sometimes referred to an an underground quarry, was opened in a 73-foot minable section of the Mahogany zone to demonstrate the feasibility of room-and-pillar mining methods, to develop and test equipment, and to determine whether low mining costs and high recovery were possible. A two-level operation was adopted: a top heading, 39 feet high; and a bench, 34 feet high.
>
> Room openings and roof-supporting pillars were both 60-feet square. An extraction ratio of 75 percent head and side space thus was sufficient to permit the use of large portable diesel and electrically driven mining equipment, thereby obtaining a high output per man-shift. An average of 150 tons per man-shift was achieved for sustained periods during normal operating tests. Special equipment developed for mining the high faces included drilling jumbos, a rotary drill for the benching operations, explosives-loading platforms, scaling rigs, and a mobile compressor and utility station. An electric shovel with a 3-cubic-yard dipper was used to load the broken shale. Diesel-powered dump trucks were used for haulage. Subsequent shale work by industry has followed in general the mining method demonstrated by the Bureau, but has incorporated equipment modernization and improvements in techniques.
>
> If an underground oil shale mining operation were to be undertaken in the near future, it could be expected to incorporate improvements over the Bureau's demonstration mine, such as the following: changing to rotary drilling in the mine heading as well as in benching; blasting with a more economical explosive, such as an ammonium nitrate-fuel oil mixture; use of modern haulage and loading equipment, and other improvements based on recent advances in quarry and open pit mining engineering. Also, in the interest of safety, a retreat system might be used instead of the advance system that was demonstrated."

Room and pillar mining techniques have been improved through subsequent work by Union Oil Company (1956-1958), Colorado School of Mines Research Foundation

(1964-1967), the Colony Development Corporation (1965-present). In considering the future, the Bureau of Mines stated:(2)

> "The room-and-pillar mining system is the only one that has been tested on the oil shales of the Green River Formation. However, open pit mining, highly developed for mining other ores, probably will be practical for oil shale in areas where conditions are favorable. Among the considerations that would be important in selecting a suitable site would be the availability of a satisfactory area for storing the overburden and the ratio of the overburden to the shale to be mined."

As regards surface mining methods for oil shale, very little information is available because so little experience has been gained in this area. However, these methods should not differ much from the coal strip mining or hard-rock open pit mining in its major aspects.

Whatever the method of mining, disposal of spent shale after surface retorting will present problems. Proposed disposal methods are underground mining with either underground disposal or surface disposal, and surface mining (strip or open-pit) with backfill.

Orehandling and Pretreatment

A schematic of the underground mining and associate surface oil shale processing units is provided in Figure 3. As seen, the operation requires primary, secondary, and sometimes tertiary crushers. Dust from crushers may be led through hooded systems and collected for proper disposal. Mine water which is of very low grade must be treated and properly disposed. Detailed data on effluents or emissions are not available and are thus suggested as areas for further research.

State of the Art

The state of the art of shale mining as regards underground mining is akin to underground coal mining. However, the art of surface ore handling operations is not very well defined nor advanced. The reasons are obvious; there has not been sufficient impetus for advancement. Present energy shortages and associated increases in liquid fuel costs

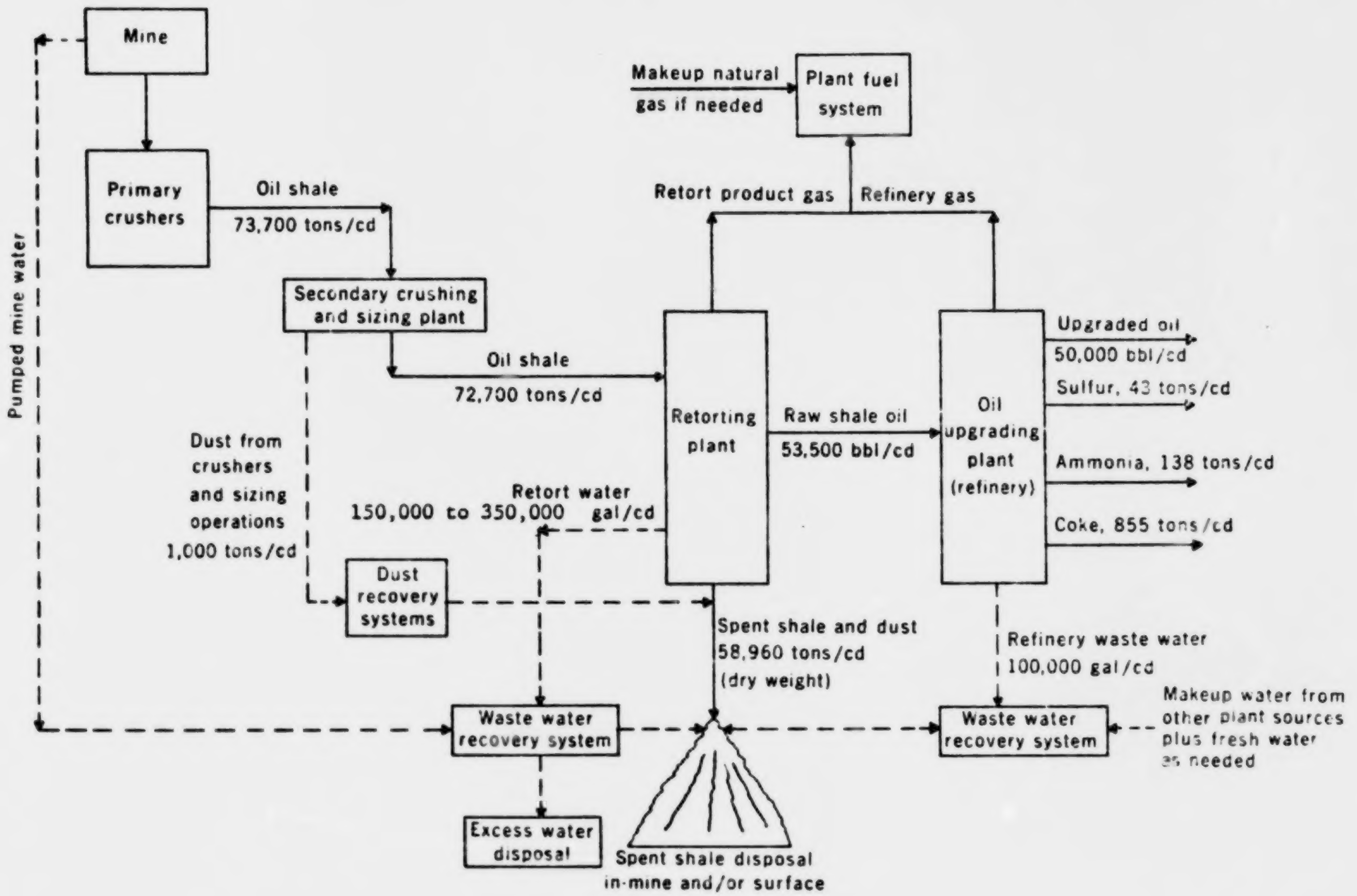
Mine
Primary crushers
Oil shale
73,700 tons/cd
Secondary crushing and sizing plant
Oil shale
72,700 tons/cd
Dust from crushers and sizing operations 1,000 tons/cd
Dust recovery systems
Retort water
150,000 to 350,000 gal/cd
Retorting plant
Raw shale oil
53,500 bbl/cd
Oil upgrading plant (refinery)
Upgraded oil
50,000 bbl/cd
Sulfur, 43 tons/cd
Ammonia, 138 tons/cd
Coke, 855 tons/cd
Makeup natural gas if needed
Plant fuel system
Retort product gas
Refinery gas
Spent shale and dust
58,960 tons/cd
(dry weight)
Refinery waste water
100,000 gal/cd
Waste water recovery system
Waste water recovery system
Makeup water from other plant sources plus fresh water as needed
Excess water disposal
Spent shale disposal in-mine and/or surface
Pumped mine water

FIGURE 3. FLOW DIAGRAM OF 50,000-BARREL-PER-DAY UNDERGROUND OIL SHALE MINE AND PROCESSING UNIT

have spurred the need for oil-shale industry growth. Consequently, there is now sufficient incentive for development of modernized methods of surface treatment of ore. Proper environmental controls should be instituted after careful deliberations in this area of shale processing.

Nature of Products

The only product from the mining and ore handling operations is the prepared oil-shale of size and grade suitable for charging to retort for oil recovery. Some retorts like the TOSCO retort can handle all fines very efficiently. For such retorts briquetting of fines is not necessary. Greater than 90 percent of mine-run shale (before crushing) is larger in size than one-inch. The required size for different retorting methods is not clearly defined in published data. However, the smaller the size required the greater the chances of dust emissions during crushing. Some types of retorting can handle minus $\frac{1}{4}$ inch shale while others (TOSCO) need $\frac{1}{64}$ inch or smaller. The limited nature of available data does not permit a detailed evaluation of this aspect.

Environmental Impacts

The major environmental impacts resulting from oil-shale handling and pretreatment are discussed below.

The generation of dust from crushing and associated operations and from the transportation of ore to the crushing facilities is the major impact on air. In the case of an underground mine, the primary crushing and grinding facilities would almost certainly be located in the mine as soon as enough space was developed to make it possible. It has been estimated that in the case of surface processing (crushing and screening) overall dust losses would be 1.3 percent of the shale handled. Except for an estimated 16 kilograms (35 pounds) per hour of dust actually lost to the atmosphere as true airborne particles from a 50,000 barrel/day plant, the dust loss from the process flow streams would be collected periodically, dampened, and disposed of with spent shale from the retorting plant.(5)

Figure 4 shows some of the surface ore handling operations necessary prior to charging the oil shale to the retort. Since the equipment used comprises conventional crushers and screens, control of fugitive dust from this equipment can be achieved by employing suitable hooding and dust control techniques. It is estimated that this method may significantly reduce the 1.3 percent dust emission to less than 0.2 percent.

It is conceivable that with the full scale development of the oil-shale industry, even the lowest dust emissions could cause health problems to the immediate populace due to the high mineral content (70 percent) of the dust. This area needs investigation.

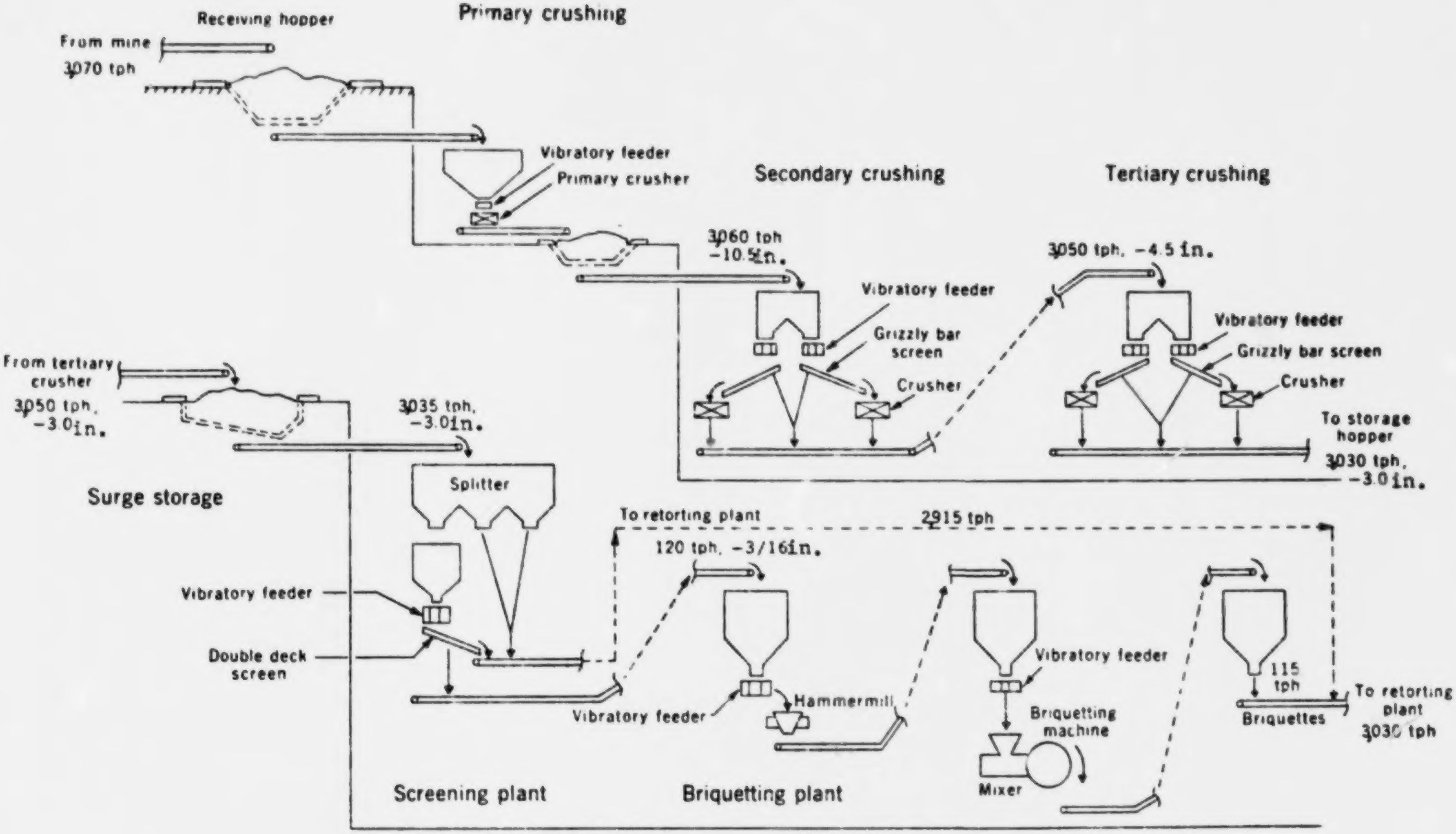
Primary crushing
Receiving hopper
From mine
3070 tph
Vibratory feeder
Primary crusher
Secondary crushing
Tertiary crushing
3060 tph
-10.5 in.
Vibratory feeder
Grizzly bar screen
Crusher
3050 tph, -4.5 in.
Vibratory feeder
Grizzly bar screen
Crusher
To storage hopper
3030 tph,
-3.0 in.
From tertiary crusher
3050 tph,
-3.0 in.
3035 tph,
-3.0 in.
Surge storage
Splitter
To retorting plant
2915 tph
120 tph, -3/16 in.
Vibratory feeder
Double deck screen
Vibratory feeder
Hammermill
Vibratory feeder
Briquetting machine
Mixer
115 tph
Briquettes
To retorting plant
3030 tph
Screening plant
Briquetting plant

FIGURE 4. CRUSHING, SCREENING, AND BRIQUETTING PLANTS - SCHEMATIC FLOW DIAGRAM (Two Identical Plants)(5)

IV. IN-SITU METHODS OF OIL RECOVERY

In-situ experiments have been conducted by private companies and the Bureau of Mines for a period of years.(5) This process involves underground heating by such means as combustion in the formation, introduction of hot natural gas, and introduction of superheated steam. However, technology has not yet developed to warrant prediction of its technical or economic success.

Process Description

A key problem is the creation of permeability within the shale matrix. Two major approaches are in the early stages of investigation. One approach proposes limited fracturing by conventional means (electric, hydraulic, and chemical explosives) whereas the other proposes massive fracturing by a nuclear explosion.

A design concept for conventional in-situ retorting based upon contemporary petroleum technology is shown in Figure 5. The essential steps include: (1) well drilling, (2) fracturing to permit heat transfer and movement of liquids and gases, (3) application of heat, and (4) recovery of products.

Remote control from the surface of the in-situ process with sufficient accuracy through wellbores is a problem still unsolved. The state of the art reviews some of these problems.

State of the Art

Sinclair Oil and Gas Company (recently merged into Atlantic Richfield Company) experimented with conventional in-situ retorting of oil shale in 1953 and 1954 at a site near the southern edge of the Piceance Creek Basin. From these tests it was concluded that communication between wells could be established through induced and natural fracture systems, that wells could be ignited successfully although high pressures were

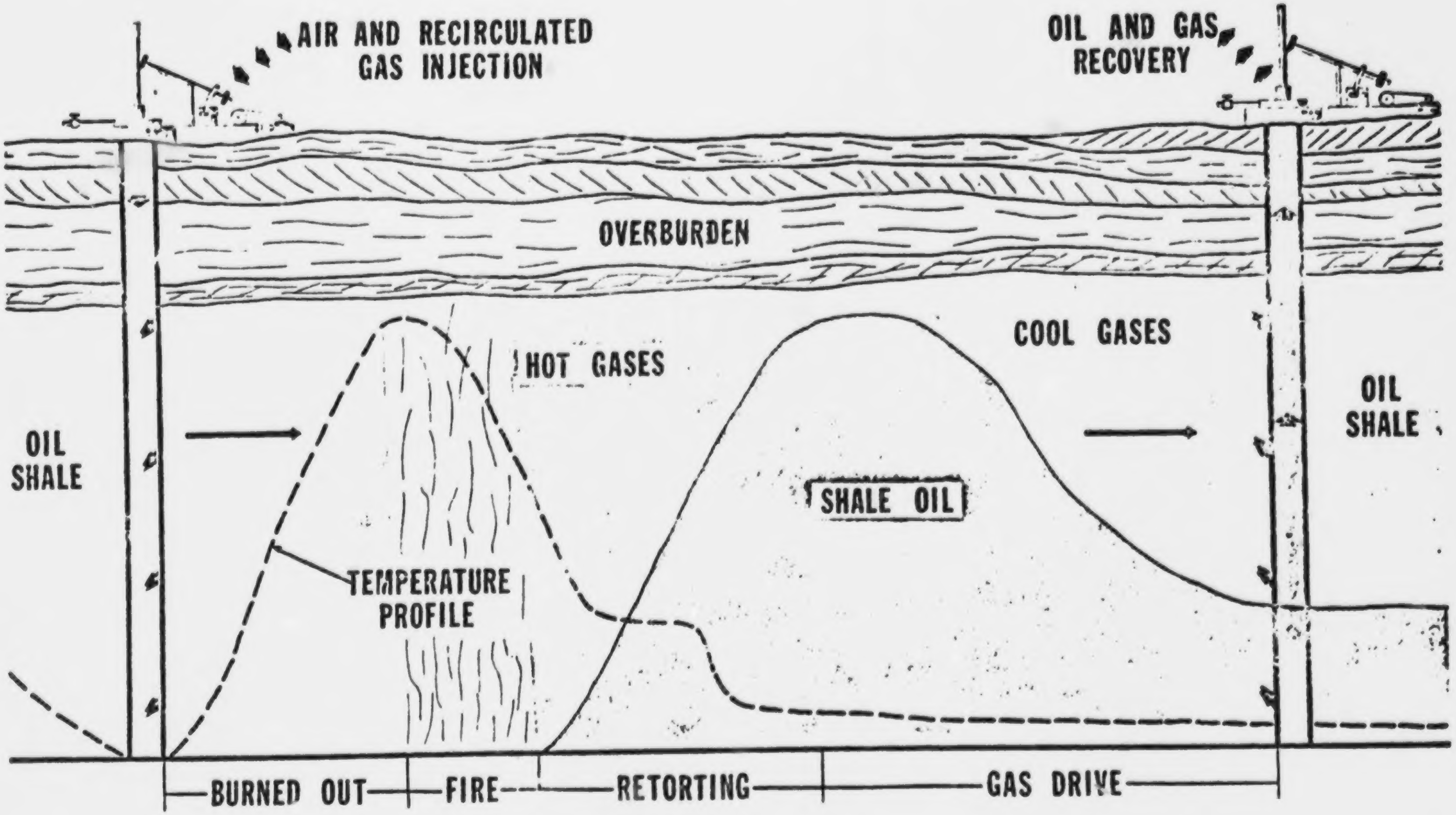
AIR AND RECIRCULATED GAS INJECTION
OIL AND GAS RECOVERY
OVERBURDEN
HOT GASES
COOL GASES
OIL SHALE
OIL SHALE
SHALE OIL
TEMPERATURE PROFILE
BURNED OUT
FIRE
RETORTING
GAS DRIVE

FIGURE 5. SCHEMATIC REPRESENTATION OF AN IN-SITU RETORTING OPERATION(5)

required to maintain injection rates during the heating period, and that combustion could be established and maintained in the shale bed.(7) Over a period of several years in the mid-1960's, Sinclair conducted field research on the in-situ process at a site near the center of the Piceance Creek Basin where the shale was much deeper and thicker than it was at the site of the first experiment. The results of this experiment were not promising; fracturing techniques that were used did not produce sufficient heat transfer surfaces for successful operation.(8,9)

Also in the 1960's Equity Oil Company conducted field experiments on in-situ processing of oil shale in the Piceance Creek Basin. The process employed the injection of hot natural gas to retort the oil shale rather than using underground combustion. However, the experiment suffered large gas losses to the formation.(10)

Several less extensive investigations of the in-situ technique have been conducted by various oil companies during the last ten years, but very little has been published concerning the results achieved.

The possibility of utilizing a nuclear explosive to fracture oil shale in preparation for in-situ retorting has been under consideration since 1958. A feasibility study for a nuclear experiment was proposed for the Piceance Creek Basin.(11) Later a similar experiment was proposed for the Uinta Basin.(12) Neither of these experiments is being actively considered at the present time. The lack of firm data precludes further analysis of this technique at this time. If such a project is proposed on public lands, it will require a complete environmental analysis, including the preparation of an environmental impact statement specifically addressed to this subject. Factors that must be considered, such as ground motion and containment of radioactivity released from the explosion, have been discussed in detail in the concept documents referenced above.(11,12)

A commercial in-situ processing system has not been demonstrated to date, but a number of field-scale experiments involving wellbores from the surface have been conducted by government and industry during the past 20 years.

Two major problems encountered from such processing are: (1) insufficient naturally occurring permeability or failure to artificailly induce permeability so as to allow passage of gases and liquids, and (2) inability to remotely control the process with sufficient accuracy through wellbores from the surface. Besides surface wellbores, other methods proposed for introducing heat underground include mine shafts, tunnels, and fractures created by a variety of techniques.

It is obvious that considerable further technological improvements must be made before industrial-scale, in-situ recovery of shale oil could become a reality.

Nature of Products

Available information suggests that oils from in-situ retorting may be somewhat superior in quality to those produced from surface retorting. Specifically, they appear to have lower pour points, viscosities, and nitrogen contents. This is illustrated by comparing the data shown in Table 2(13) with data on characteristics of ex-situ recovered oil as presented in Tables 5 and 7 of Section V. In-situ oil may be marginally suitable for transporting without upgrading because of the low pour point; however , no firm conclusions are possible because of insufficient data.

Gases produced in the gas/oil separation step would have the characteristics shown in Table 3.(13) These data indicate that nearly 95 percent of the gas components have no value as fuel. From these scant data, it can be said that in-situ retorting does not generate gas which is useful as fuel. However, since the gases will be hot and have some fuel value, it may be possible to recompress the gases and use it for in-situ retorting by pumping into formations.

Data on the concentration of dust in gases are not available.

Process Efficiency

Very little data are published on the efficiency of the in-situ process. If some guesses may be made, since in-situ retorting is so unlike

TABLE 2. CHARACTERISTICS OF OILS FROM IN-SITU RETORTING(13,27)

	Bureau of Mines(a)	Sinclair(a)	Equity(b)	Bureau of Mines(a)
Gravity, API	31.7	30.6	54.2	28.4
Sulfur, wt %	0.67	1.28	0.61	0.60
Nitrogen, wt %	1.35	1.14	0.36	1.69
Pour Point, F	+5	+35	-15	10
Viscosity, SUS @ 100 F	41.0	--	--	45

(a) Heat supplied by underground combustion.

(b) Heat supplied by introduction of hot natural gas to formation.

TABLE 3. CHARACTERISTICS OF GASES(a) FROM IN-SITU RETORTING(25)

Component	Concentration, mole percent(b)
Nitrogen	77.2
Oxygen	10.1
Propane	0.2
Carbon Dioxide	9.9
Carbon Monoxide	0.8
Hydrogen Sulfide	NR(c)
Butanes	NR
Methane	1.2
Ethane	0.6

(a) Heating value approximately 30 Btu/scf. Yield from operation at level of 50,000 bbl/CD. Upgraded shale oil approximately 1,485 x 10^6 scf/CD.

(b) Concentrations reported on a water-free basis.

(c) NR: Not reported.

the ex-situ, in that it does not require crushing, grinding, screening and associated process and pollution control equipment, the overall economic efficiency should be higher if a cheap means of fracturing and mine retorting can be found. Nuclear energy may represent this cheap means, but the adverse environmental consequences of nuclear fracturing are still not evaluated.

Losses of agents injected to promote underground combustion have been common. In addition, the recovery of the oil content of the shale will not be as high as in ex-situ retorting. These factors will hinder full resource utilization.

In summary, the state of the art of in-situ processing is very elementary and it is too early to make any judgments.

Environmental Considerations

In-situ recovery of oil does involve considerable above ground activity. A conceptual scheme for the Wyoming tract in-situ operations, shown in Figure 6, illustrates the dynamic nature of in-situ processing. It is estimated that the two tracts would require multiple rows of 100 wells, which would be drilled on a monthly basis. Five rows of wells (100 each), comprising restoration, plugging, injecting, producing, and drilling operations, would consume about 115 acres of active area at any one time. This active area would progressively move forward as new wells were drilled. It would take approximately 3 years for restoration to be complete.

Impacts on air and solid waste by in-situ processing cannot be estimated until the status of development of the processes is such as to provide data on products, by-products and wastes produced. It will be necessary to hold direct conversations with developers of in-situ techniques and visit in-situ testing facilities to obtain first hand understanding of the problems associated with in-situ processing. From such an understanding reasonable estimates of environmental impacts can be made and steps taken to insure minimal adverse environmental impacts.

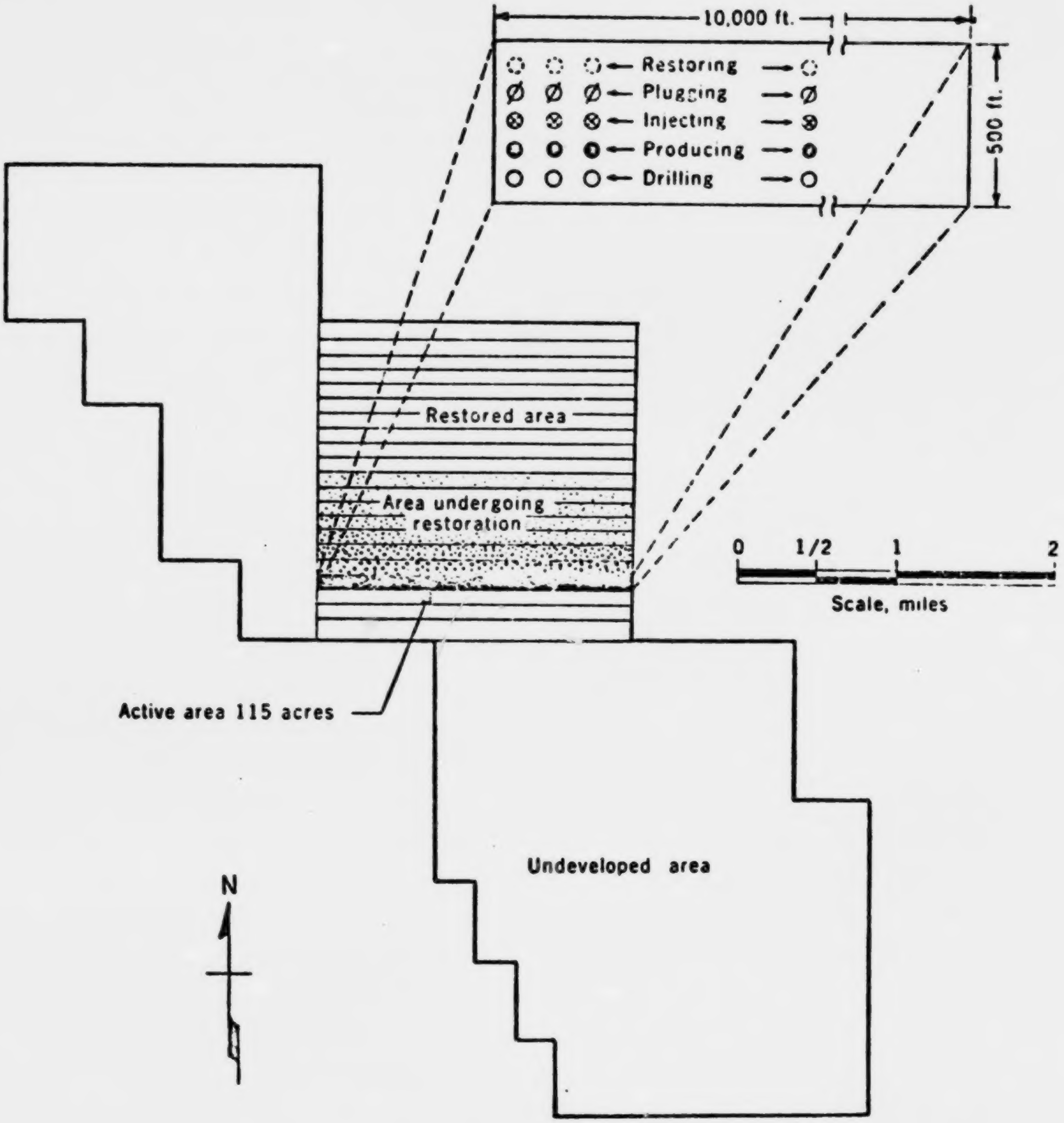
10,000 ft.
500 ft.
Restoring
Plugging
Injecting
Producing
Drilling
Restored area
Area undergoing restoration
Active area 115 acres
Undeveloped area
0
1/2
1
2
Scale, miles
N

FIGURE 6. WYOMING W-a AND W-b IN-SITU RECOVERY - CONCEPTUAL DEVELOPMENT APPROACH(5)

V. EX-SITU RETORTING

Above ground thermal processes for extracting crude shale oil from mined shale are divided into four types according to the method of heat transfer.

Type 1. Indirect heating through the wall of the retorting vessel. (There are no active processes in this category.)

Type 2. Direct heating by hot gases through combustion within the retorting vessel.

- Gas-Combustion Process (Bureau of Mines)
- Union Oil Process (Union Oil Company of California)

Type 3. Heat transfer from an externally-heated carrier fluid.

- Petrosix (Cameron and Jones Vertical Kiln)

Type 4. Heat transfer from recycled hot solids.

- TOSCO Process (The Oil Shale Corporation).

Each type is analyzed by comment on the following aspects: (a) process description; (b) state and scale of current development, i.e., pilot plant, prototype, or commercial scale; (c) products and yield of shale oil produced and physical properties of the crude oil; (d) thermal, yield, and economic efficiencies; (e) pollution aspects of the preretorting, retorting, and post-retorting operations; and (f) expected commercial utilization.

The various retorting procedures for extracting shale oil generally consist of three steps as follows:

1. Preretorting - consists of operations such as crushing, screening, briquetting, and suitable sizing of oil shale for charging to retorting units.
2. Retorting - consists of heating the oil shale to or above the pyrolyzing temperature, approximately 480 C (900 F), separation of oil from the retort gases, removal of spent oil-shale residue from the retort and preparing the heat transfer medium for

recycle. In some types of retorting, a heat transfer medium is not employed; instead, low Btu gas from the retorting step is used for direct firing of the retort.

3. Post-retorting - consists of upgrading of the crude shale oil obtained in Step 2. Usually thermal and/or hydrogenation methods are employed for upgrading.

Heat required for retorting is estimated(8) in one process to be 1.4 million Btu per ton of oil-shale charge. Better heat transfer techniques can reduce the heat requirement, thus the classification on the basis of the method of heat transfer employed. A general schematic of a retorting system is provided in Figure 7.

Gas Combustion Process (Type 2)

Process Description

The Bureau of Mines gas combustion retorting process is characterized by its use of continuous gravity flow of shale and direct gas-to-solids heat exchange by a heat source from internal combustion. The essentials of the process are illustrated in Figure 8. The retort is a vertical, refractory-lined shaft equipped with shale and gas-handling devices. Crushed and sized shale, (approximately 0.25 to 3 inches, 0.7 to 7 cm), moves downward as a bed through the retort vessel, entering through the product cooling zone where some of the organic matter is decomposed by heat to liberate oil vapor and gas. A carbonaceous residue from the decomposition reaction remains as part of the shale particles. The shale next proceeds to the combustion zone, where sustaining heat for the process is produced by burning the organic residue on the shale at temperatures of 480-760 C (900-1400 F). A part of the product gas is returned to the system to provide heat for the retorting zone. From this hot zone, the shale moves down through the heat recovery zone where its heat is transferred to the rising stream of recycle gas. The cooled, spent shale (of approximately the same physical size as the charged shale) at about 94 C (200 F) is mechanically discharged from the retort at a controlled rate.

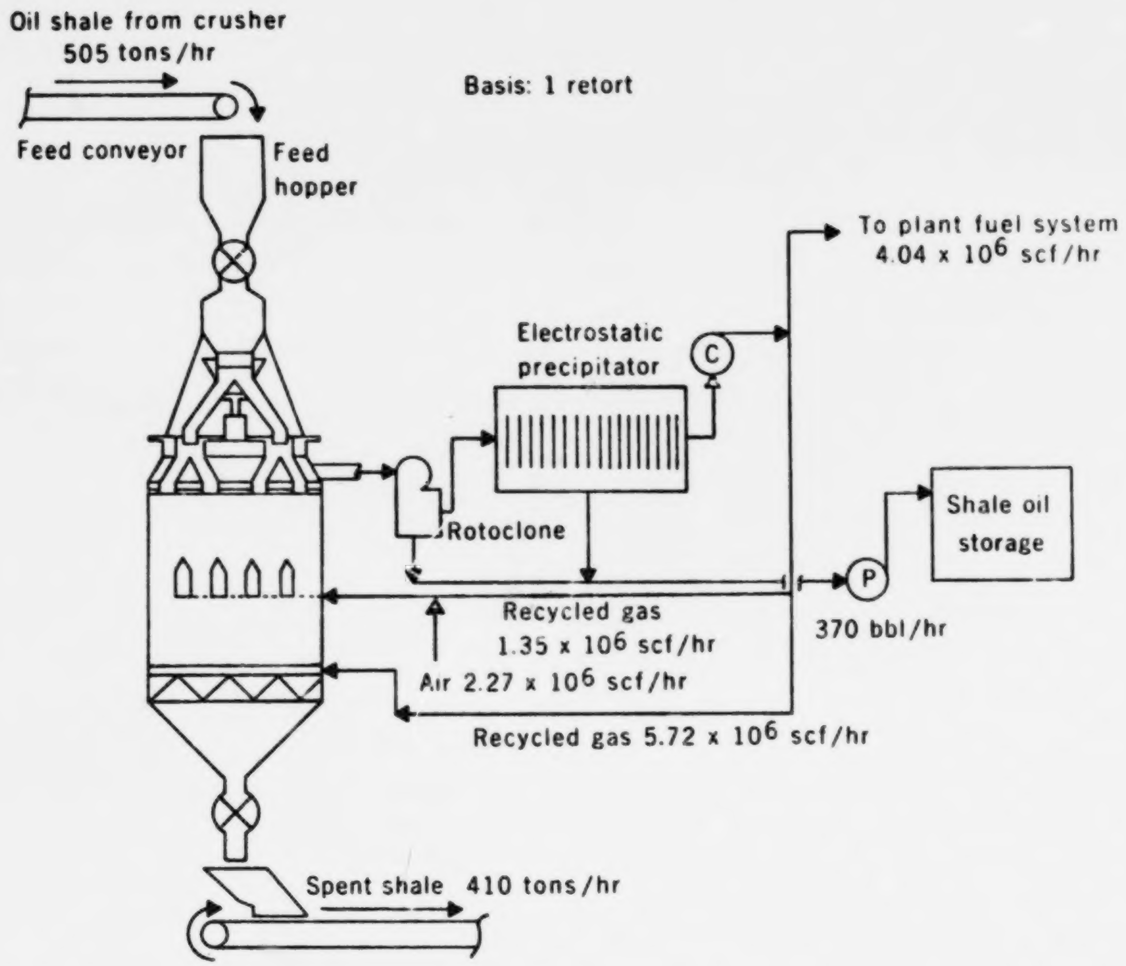
Oil shale from crusher
505 tons/hr
Basis: 1 retort
Feed conveyor
Feed hopper
To plant fuel system
4.04 x 10^6 scf/hr
Electrostatic precipitator
C
Rotoclone
Shale oil storage
P
Recycled gas
1.35 x 10^6 scf/hr
370 bbl/hr
Air 2.27 x 10^6 scf/hr
Recycled gas 5.72 x 10^6 scf/hr
Spent shale 410 tons/hr

FIGURE 7. SCHEMATIC FLOW DIAGRAM OF RETORTING SYSTEM
Note C: Compressor
P: Pump

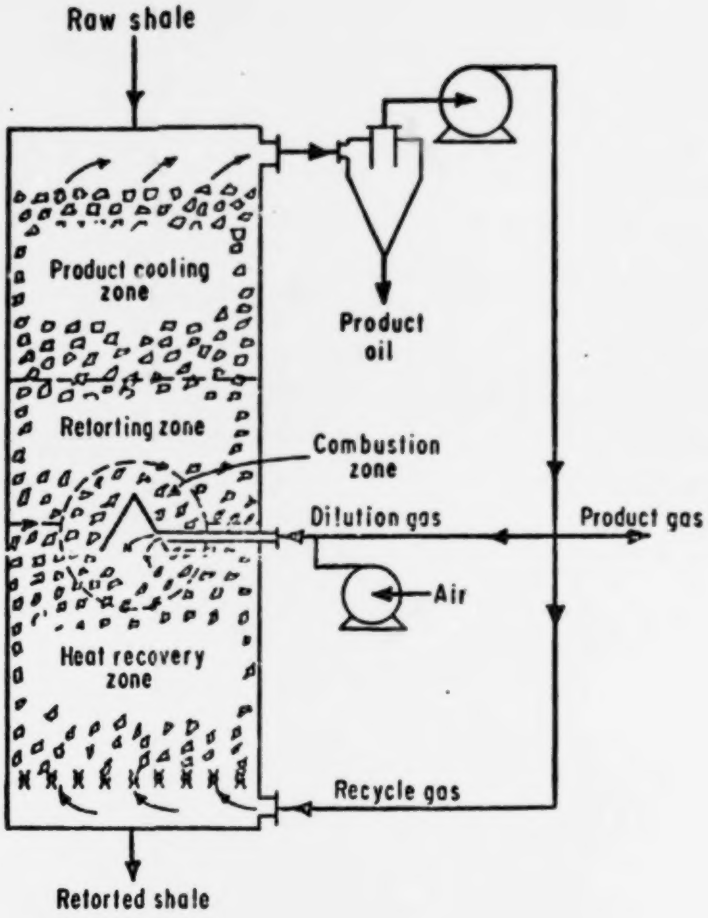
Raw shale
Product cooling zone
Retorting zone
Combustion zone
Dilution gas
Product gas
Product oil
Air
Heat recovery zone
Recycle gas
Retorted shale

FIGURE 8. BUREAU OF MINES GAS COMBUSTION PROCESS

Recycle gas is injected at the bottom of the vessel and rises through the spent shale in the heat recovery zone. An air distribution device is located near the center of the retort where air, diluted with part of the circulating retort gas, is injected. This mixture is heated quickly by contact with the hot spent shale. In addition, reaction of the oxygen in the gas with combustibles produces a hot flue gas. The hot flue gases, recycle gases, and CO_2 from the decomposition of certain carbonates in the shale rise in contact with the descending raw shale in the retorting zone, and the solids are heated enough to effect thermal decomposition of the kerogen in the shale. In the product cooling zone, the oil in the gas stream is cooled below its dew point, condenses as a fine mist or fog, and is carried out of the top of the retort.

The overhead stream from the retort passes first through oil-mist separators to recover the shale oil. The oil-lean gas enters a blower and is divided into three streams. One stream (dilution gas) is injected with air into the center of the retort. A second stream (recycle gas) enters the bottom of the retort. The remainder (net product gas) is vented from the system.(2,5)

Status of Development

Working under the Synthetic Liquid Fuels Program, the Bureau of Mines developed the gas combustion retort after an extensive pilot-plant study of batch-type and moving-bed retorts. The first gas combustion unit was a 5.4 kkg/day (6 ton/day) pilot plant built in 1950 which was followed by construction of a 22.7 kkg/day (25 ton/day) pilot plant and a 136 kkg/day (150 ton/day) demonstration plant. These units were operated on a development and demonstration basis until they were put on a standby status in 1955.

The Anvil Points facilities were reactivated in 1964 for further process studies under a lease agreement with the Colorado School of Mines Research Foundation. Six petroleum companies sponsored this project both financially and technically. These were Mobil Oil Corporation, Humble Oil and Refining Company, Pan American Petroleum Corporation, Sinclair Research, Inc. (Atlantic-Richfield), Continental Oil Company, and Phillips Petroleum Company. Their operation extended over a period of 3 years from 1964-1967. They demonstrated that yields in excess of 85 percent of Fischer assay could be obtained at feed rates of 226 kg/hr (500 lb/hr) per square foot of bed cross-sectional area. This was about double the rate previously demonstrated by the Bureau of Mines.(14) This expansion in capacity resulted in a large retort capacity of 326.5 kkg/day (360 ton/day). Commercial production at the 50,000 bbl/day level would require 6 individual retorts(2) of 458 kkg/hr (505 ton/hr) capacity. Therefore the existing state of development is close to the ultimately required process equipment. The additional research indicated that a material advance in processing technology had been accomplished. Some operating problems associated with scale-up are still unresolved, e.g., even downward flow of shale in large diameter retorts and prevention of channeling of the rising gases are still problems.

Nature of Products

Oil. Yields from the large 136 kkg/day (150 ton/day) demonstration unit dropped by about 8 percent below the yields of 94-95 percent obtained in the 5.4 kkg/day (6 ton/day) plant.(4) The larger demonstration plant at shale feed rates up to 326.5 kkg/day (360 ton/day) averaged yields of 82-87 percent.(1) Although examination of the retorted shale indicated that retorting efficiency was high, a study of product oil indicated that the lower efficiency was the result of more extensive secondary cracking of the oil produced in the larger scale unit.

Crude shale oils produced from surface retorts may generally be classed as low-gravity, moderate-sulfur, high-nitrogen oils compared to petroleum crudes. Generally shale-oils are more viscous, higher pour point (congealing temperature) oils than many petroleum crudes. Oils differ by different retorting methods; properties of the oil produced by the gas combustion process are noted in Table 4.

Gas. The retort gas produced from the gas combustion process is diluted with the products of combustion, carbon oxides from the decomposition of carbonates in the shale, and inert components of the air introduced to support combustion.

Characteristics and yields of untreated retort gas typical of this internal combustion process are presented in Table 5.

Spent Shale. The spent oil shale has relatively low carbon residue (approximately 3 weight percent), and is of approximately the same size, 0.6 cm (0.25 inches), as the charged shale.(1) Some of the shale, of course, will be crushed as the shale moves downward through the retort, and the resulting fines will be entrained with the rising gas stream and carried off with the product vapors. The large size of spent shale will facilitate ease in transportation and ultimate disposal and will require less water for dust control during the disposal operation. The gas combustion process can be said to have an advantage as far as spent shale size is concerned.

TABLE 4. PROPERTIES OF CRUDE SHALE OIL PRODUCED BY THE GAS COMBUSTION PROCESS(5)

Gravity, API	19.7
Sulfur, wt %	0.74
Nitrogen, wt %	2.18
Pour Point, C (F)	28 (80)
Viscosity, Centistokes at 38 C (SUS at 100 F)	55.3 (256)

TABLE 5. PROPERTIES OF RETORT GAS FROM THE GAS COMBUSTION PROCESS(5)

Composition	Volume percent
Nitrogen	62.1
Carbon monoxide	2.3
Carbon dioxide	24.5
Hydrogen sulfide	0.1
Hydrogen	5.7
Hydrocarbons	5.3
Gross heating value	
kcal/scm (Btu/scf)	900 (100)
Molecular weight	30
Yield, scm/bbl oil (scf/bbl oil)*	309 (10,900)

* Standard cubic foot of gas per barrel of oil produced.

Process Efficiency

Thermal Efficiency. The gas combustion process internal temperatures rise above 480 to 760 C (900 to 1400 F) in the area of the combustion zone. The dolomite ($CaCO_3 \cdot MgCO_3$) in oil shale begins to decompose somewhat below 540 C (1050 F) yielding magnesium oxide, carbon dioxide, and calcite. The calcite ($CaCO_3$) - both that in the oil shale and that produced by the dolomite decomposition - begins to dissociate in the range of 620-650 C (1150 to 1200 F). In addition, other compounds, e.g., nahcolite ($NaHCO_3$), also decompose at these temperatures. All these reactions are endothermic, and their decomposition places additional heat demands on the gas combustion process, ultimately lowering its overall thermal efficiency. Specific values for thermal efficiency are not presently available.

Product Yield. The yield of oil produced from the small pilot plant was about 95 percent; the yield on the large 136 kkg/day demonstration size unit fell to about 87 percent and to 85 percent in the 326.5 kkg/day plant. This yield relationship extrapolated to commercial scale (50,000 bbl/day) indicates a further drop to 78 percent of Fisher assay. In addition to the lower oil yields, the vertical kiln configuration will force lower raw shale utilization. In order to avoid an excessive pressure drop when forcing the hot gases through the shale bed, it will be necessary to limit the particle size to 1.3 cm (0.5 inch) or larger. The expansion to commercial scale retorts will increase this minimum particle size, necessitating the exclusion of fines and an auxiliary briquetting operation. In either case the inability to accept all sizes of shale input, especially fines, must be considered an economic weakness of the gas combustion process.

Costs. The efficiency or inefficiency of the gas combustion process will ultimately reflect in the capital and operating costs. The lower yields reported (and predicted) for oil produced and the poor shale utilization will dictate higher mining expenditures, construction of larger, more expensive retorting units, and necessitate raw material wastage or additional auxiliary operations. The dilution of the product gases with both combustion and decomposition gases will require all or a very large percentage of the retort gas to be recycled for internal heating purposes; and gases which are available will be of a somewhat limited use. Therefore, additional energy sources for other heat-requiring operations seem to be needed to operate the facility.

Since water is not required for cooling or elsewhere, this process will be efficient in the water demand sense. Some water will have to be imported for use in shale disposal. However, since the crushed and final retorted size of the shale will be relatively large, the increase in specific volume of the retorted shale is not excessive; therefore, the water requirements and the disposal area necessary will be somewhat minimized.

No estimation of capital or operating costs for retorting facilities utilizing the gas combustion process is available.

Environmental Considerations

Preretorting. The main influence the gas combustion process will have on the preretorting facilities will be the input particle size. As noted earlier, the chunks of oil shale must be larger than a minimum size of about 1.3 cm (0.5 in.) for efficient operation. The effect will be to allow the crushing, screening, and conveyance of relatively large pieces of oil shale to be accomplished with a minimum of air pollution (dust). However, this same minimum size requirement could lead to the creation of a solid waste problem (oil shale fines) if the fines are not compacted for use, since use of fines as such in this process is difficult.

Retorting. The retorting operation produces a gaseous stream containing the crude shale oil and other gases. This overhead stream has value as a fuel source; hence, this stream must be economically and adequately controlled. The particulates in the gases can suitably be removed. Most of the gas stream is recycled to the retort. Commercial considerations generally envision the product gas being used as a fuel for generation of power and process stream. Regardless of the manner in which the retort gases were burned to utilize their fuel values, sulfur control would be required to meet air quality standards. In this regard, existing methods of treatment for gas desulfurization can be investigated. The sulfur concentration in the gas combustion process gases are so low that desulfurization may not prove economical. This aspect needs careful investigation.

From the bottom of the retort, spent oil shale will be discharged. This discharge will be large (51,700 kkg/day or 57,000 ton/day), hot (94 C, or 200 F), and likely to be associated with steam and other minor gaseous emissions. Special provisions will be needed to avoid air pollution while transporting the spent shale, and its environmental, economic, and technical aspects will be discussed in greater detail in another section of this report.

Expected Commercial Development

The gas combustion process, although not the most advanced, has several positive factors supporting possible commercial development. The Bureau of Mines has operated a large demonstration scale unit. Years of extensive process development have gone into the refinement of this process. Such development has not advanced to the degree where reasonably accurate scale-up to a commercial sized facility, employing multiple units, is possible. The gas combustion process is the most advanced government sponsored oil shale retorting process. In addition to Federal support, six major oil companies have invested significant quantities of time and money into the further development of this process. As displayed by the current levels of bidding for Federally owned oil shale tracts ($210.3 million for the right to experimentally develop the first 2065 hectare* tract) significant interest has now been placed by the major oil companies in the oil shale resources. Plans for a 50,000 to 100,000 bbl/day facility (employing this and other retorting methods) are now being prepared.(15)

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* About 5000 acres.

The Union Oil Process (Type 2)

Process Description

The Union Oil Company of California retorting process is characterized by its use of an under-feed flow of shale, direct gas to solids countercurrent heat exchange, and heat supply by internal combustion. The essentials of the process are illustrated in Figure 9. The retort is a vertical, refractory-lined conically shaped kiln equipped with a unique shale charging device, and gas handling equipment.

Crushed, sized, and screened shale of a maximum size of 12.7 cm (5 in.) and a minimum of about 0.3 cm (0.1 in.) are fed from the bottom of the retort by means of a "rock pump". Hot gases and air are pulled downward through the shale bed by suction blowers. No water is required by this retorting process.

The actual mechanism of the retorting process is described below. The processes occurring in the kiln's retorting section may be divided into three zones. In the top zone, heat exchange between incoming air and hot clinker leaving the unit is effected. In the lower portion of this top zone, the carbon residue on the spent shale is burned, producing flue gas with a temperature near 1093 C (2000 F). This flue gas is drawn downward into the retorting zone, where the shale is heated to retorting temperature and oil vapors and gas are evolved. The mixture of shale oil vapors and flue gases progresses downward into the condensation zone, where the incoming raw shale is heated and the retort products are cooled and the oil is condensed.(16)

The unique difference between the Union Oil process and the gas combustion process (both use internal combustion retorts) is the method in which the raw shale is charged to the system. Operation of this unique feed mechanism facilitated by the rock pump is illustrated in Figure 10. In Step 1 a hydraulically-operated piston retracts and the feeder cylinder fills with

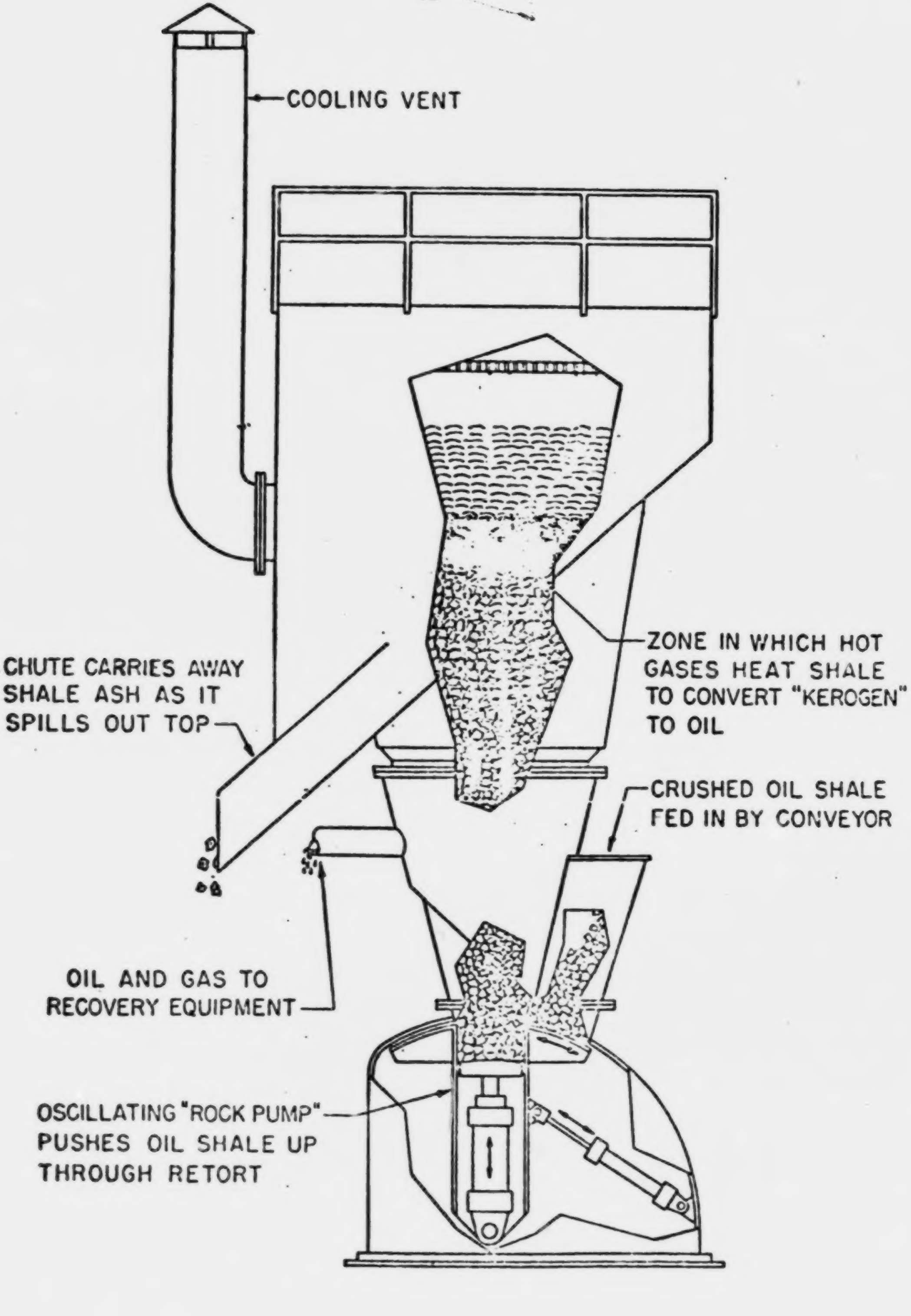
COOLING VENT
ZONE IN WHICH HOT GASES HEAT SHALE TO CONVERT "KEROGEN" TO OIL
CHUTE CARRIES AWAY SHALE ASH AS IT SPILLS OUT TOP
CRUSHED OIL SHALE FED IN BY CONVEYOR
OIL AND GAS TO RECOVERY EQUIPMENT
OSCILLATING "ROCK PUMP" PUSHES OIL SHALE UP THROUGH RETORT

FIGURE 9. UNION OIL RETORT(5)

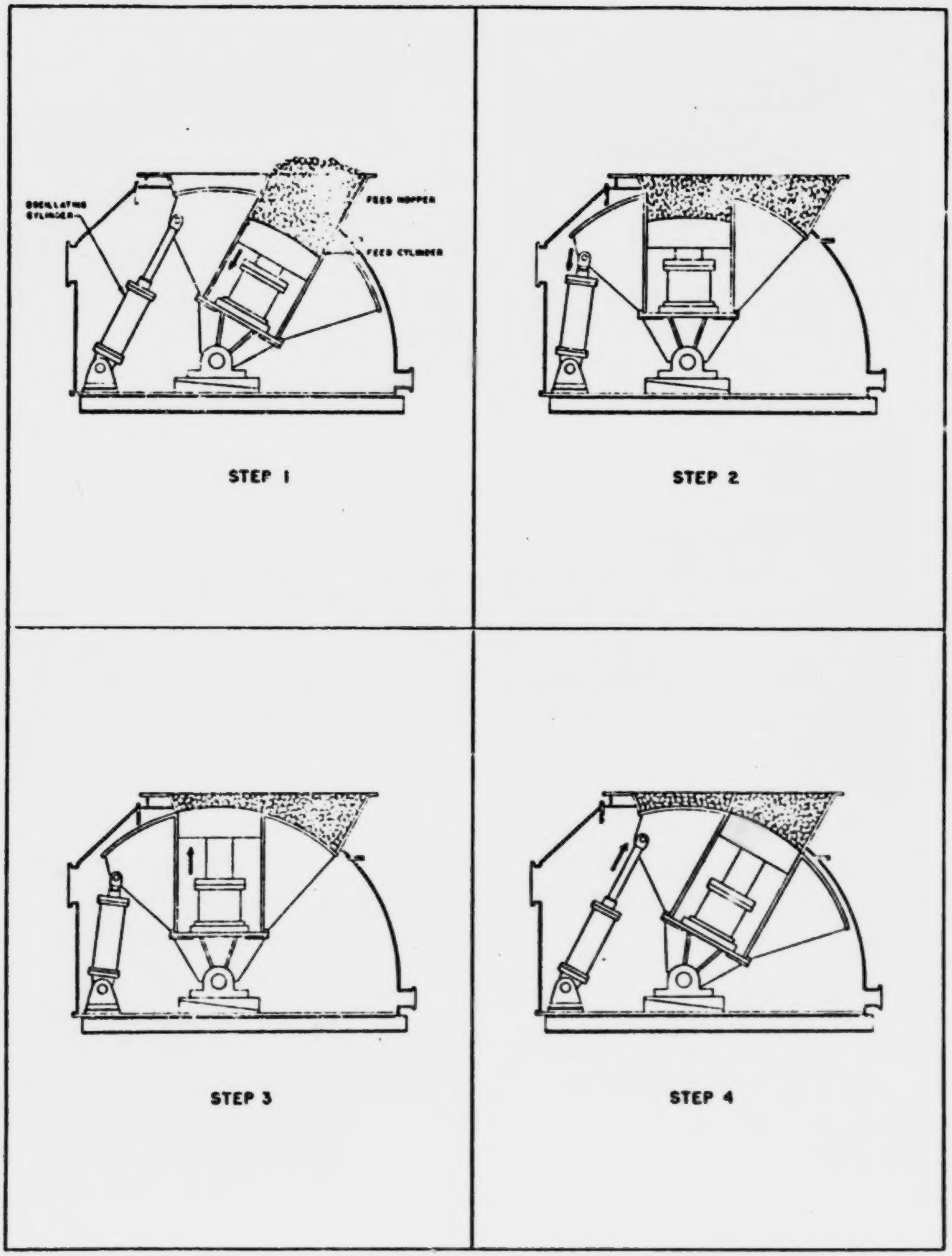
OSCILLATING CYLINDER
FEED HOPPER
FEED CYLINDER
STEP 1
STEP 2
STEP 3
STEP 4

FIGURE 10. ROCK PUMP FOR UNION OIL RETORT(5)

raw shale from the feed hopper. In Step 2 the feeder unit is rotated to a vertical position under the retort by means of the oscillating cylinder. In Step 3 the piston is extended forcing the shale into the retort, and (Step 4) remaining in the extended position, the piston is rotated back to the feed hopper ready to repeat the operation.

Status of Development

The Union Oil retort design was developed during the late 1940's by construction of a 1.8 kkg/day (2 ton/day) plant followed by a 27 kkg/day (30 ton/day) pilot plant. In 1956 a demonstration plant was built on the company's oil shale properties in Parachute Creek, Colorado.

A further increase in experimental capacity was completed in March, 1957. The original demonstration plant retort, having a feeder piston diameter of 1.7 m (5.5 feet), was designed for a capacity of 326 kkg/day (360 ton/day). Further development and demonstration of the facility through August, 1958 allowed throughput rates to be increased to as high as 1088 kkg/day (1200 ton/day). Operation at rates near this level was obtained on an automatic control basis for continuous periods up to six weeks.

The research facility was closed in 1958, but by that time Union Oil was sufficiently satisfied with the success of the experiments. Published reports in 1959 stated that(17)

> "We (Union Oil) have firmly established the retorting technology to design and operate a single retort with a throughput capacity of up to 1700 tons of oil shale rock per day. Further, we believe that a single retort with a capacity of 3,000 tons/day is a reasonable extrapolation."

Individual retorting units having capacities of 9070 kkg/day (10,000) tons/day) or larger are envisioned to be the appropriate size for commercial scale retorting plants.(5) Therefore, the existing scale of development was about one sixth the expected commercial size. No reports of recent development (after 1959) of this technology have been released. However, the company, again active in the oil shale development area, has announced that larger equipment could be designed and constructed whenever the energy demand and economic conditions warrant it.(5)

Nature of Products

Oil. Yield of oil extracted from oil shale has not been reported for this large-scale UOC plant. However, the yield may be estimated as 5-10 percent below the 102 percent obtained in the original investigation.(16) Properties of the shale oil from the original Union process are noted in Table 6.

TABLE 6. PROPERTIES OF CRUDE SHALE OIL PRODUCED BY THE UNION OIL RETORT "A" PROCESS(5)

Gravity, API	20.7
Sulfur, wt %	0.77
Nitrogen, wt %	2.01
Pour Point, C (F)	32 (90)
Viscosity, Centistokes at 38 C (SUS at 100 F)	48 (223)

Gas. The retort gas produced from this process, like that of the gas combustion process, is diluted with the products of combustion, carbon oxides from the decomposition of carbonates in the shale, and inert components of the air introduced to support combustion.

Characteristics and yields of untreated retort gas typical of internal combustion processes produced at higher temperatures such as the Union Oil process are presented in Table 7.

TABLE 7. PROPERTIES OF SHALE "GAS" PRODUCED BY HIGH TEMPERATURE INTERNAL COMBUSTION RETORTING PROCESS (5)

Composition	Volume %
Nitrogen	60.1
Carbon monoxide	4.7
Carbon dioxide	29.7
Hydrogen sulfide	0.1
Hydrogen	2.2
Hydrocarbons	3.2
Gross heating value kcal/scm (Btu/scf)	747 (83)
Molecular weight	32
Yield, scm/bbl oil (scf/bbl oil)	582 (20,560)

Not noted here is the lower concentration of entrained fines in the exiting gas stream. This reduction is one of the advantages of the countercurrent flow design of this retort. The hot gas stream is drawn through the shale bed which acts as a filter to remove entrained solids.

Spent Shale. Spent shale from the Union Oil retorting process will be similar to the retorted shale from the gas combustion process, both in size distribution and most physical properties but will have only a negligible quantity of residual carbon. The relatively large size of the shale utilized combined with the agglomerates produced by the very high temperatures obtained in the retorting operation produce large chunks of spent shale, which should allow for ease in transport and disposal, and should require only moderate quantities of water for dust control and disposal.

Process Efficiency

Little direct data on the efficiency of the Union Oil Retort process have been published. However, through examination of the process requirements, certain important facts can be deduced.

Thermal Efficiency. The countercurrent flow of hot and cold material employed in this process is believed to provide a more effective heat transfer path than the countercurrent gas combustion process. The entire heat requirements of this process are obtained by the combustion of the carbonaceous matter retained on the retorted shale, thus saving the diluted product gas for power generation and other onsite requirements. Therefore, the basic heat transfer design of the Union Oil retort is considered superior to the gas combustion process.

The decomposition of the inorganic carbonates will be nearly complete in the combustion zone where the reaction temperatures are high (2000 F). Since this high temperature is not sustained in the retorting zone, the shale oil quality should not be significantly affected.

Product Yield. No data have been published on the yield of shale oil from the large-scale UOC units. However, since initial data showed a 102* percent yield, estimated commercial scale yields of 90-100 percent seem reasonable. These yields are superior to the gas combustion process yields.

Costs. The greater mechanical requirements of this process (i.e., the rock pump) could significantly raise the capital investment requirements by necessitating larger, stronger retort structures to withstand the internal pressures generated by the shale oil rock pump and more sophisticated retorts to support the greater mechanical complexity. In addition, the pumping of the shale feed could result in higher operating costs from increased abrasion, necessitating frequent and costly refractory replacements, and from additional maintenance costs of the pump itself. The expected higher yields may possibly offset some of these cost increases.

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* Yields calculated on the basis of Fisher assays frequently exceed 100 percent.

The process is internally fuel sufficient since no auxiliary fuels are required, but the charging operation will require much greater quantities of energy than a simple gravity feed configuration. The process produces a large quantity of dilute shale gas which can be converted into energy for this and other purposes. No data are available to accurately evaluate this power requirement/gas production tradeoff. However, it is believed that significant quantities of outside power will be required to operate this facility.

Like the gas combustion process, the Union Oil retort does not require water for cooling or for incorporation with the reaction mixture. Other sources of water additional to that generated by the process will be required for retorted shale disposal. However, since spent shale generated by the Union Oil process consists of large agglomerated chunks - not fine particles which require wetting before disposal, the requirement for water for proper disposal and for disposal land reclamation can be somewhat minimized.

Capital or operating cost data for retorting facilities utilizing the Union Oil process are not available in published literature.

Environmental Considerations

Preretorting. Serious air pollution, primarily dust, can be avoided in this retorting process due to the relatively large feed shale size distribution. Extensive crushing and grinding will be minimized. Shale fines, particles less than 0.3 cm (0.1 in.), will have to be compacted into acceptable size particles or disposed of carefully with the retorted oil shale.

Retorting. The pollution aspects of the Union Oil retort process will be very similar to those of the gas combustion process. The process stream containing the product oil and low Btu gas will necessarily be adequately controlled to recover the product shale oil and the valuable fuel gases. The combustion of these gases for power generation will require control to remove the sulfur oxides, most likely by standard treatment of the stack gases following combustion.

Retorted shale produced by this process will require disposal. The hot, steaming mass will need to be adequately controlled by proper conveyance methods while the shale is cooling. The large average particle size of the spent shale will allow easy transport of the clinker-like, carbon free shale to the ultimate disposal site without significant dust generation.

Expected Commercial Development

The Union Oil process, while not being actively investigated at the present time, does have several technological advantages and good potential for commercial exploitation. The Union Oil Company has demonstrated a capability of successful operation of a 1088 kkg/day (1200 tons/day) plant which is 4 times the demonstrated capacity of the gas combustion process. The plant has been operated over an extended period continuously. While certain scale-up problems are anticipated, reasons for not utilizing this technology to design and construct an efficient commercial-scale facility within a reasonable period of time are not readily apparent.

Petrosix Process (Type 3)

Process Description

Petrosix process, developed by the Brazilian National Oil Company, employs the Cameron and Jones kiln. The process is characterized by its use of continuous gravity flow of shale, direct gas-to-solid heat exchange, with retorting heat supplied by an externally heated carrier fluid (recycle gas). Except for the mode of heat transfer, this system is similar to the Bureau of Mines gas combustion process. The essentials of the process are illustrated in Figure 11. The retort is a vertical, refractory-lined shaft with a conical bottom, equipped with elaborate shale and gas handling devices.

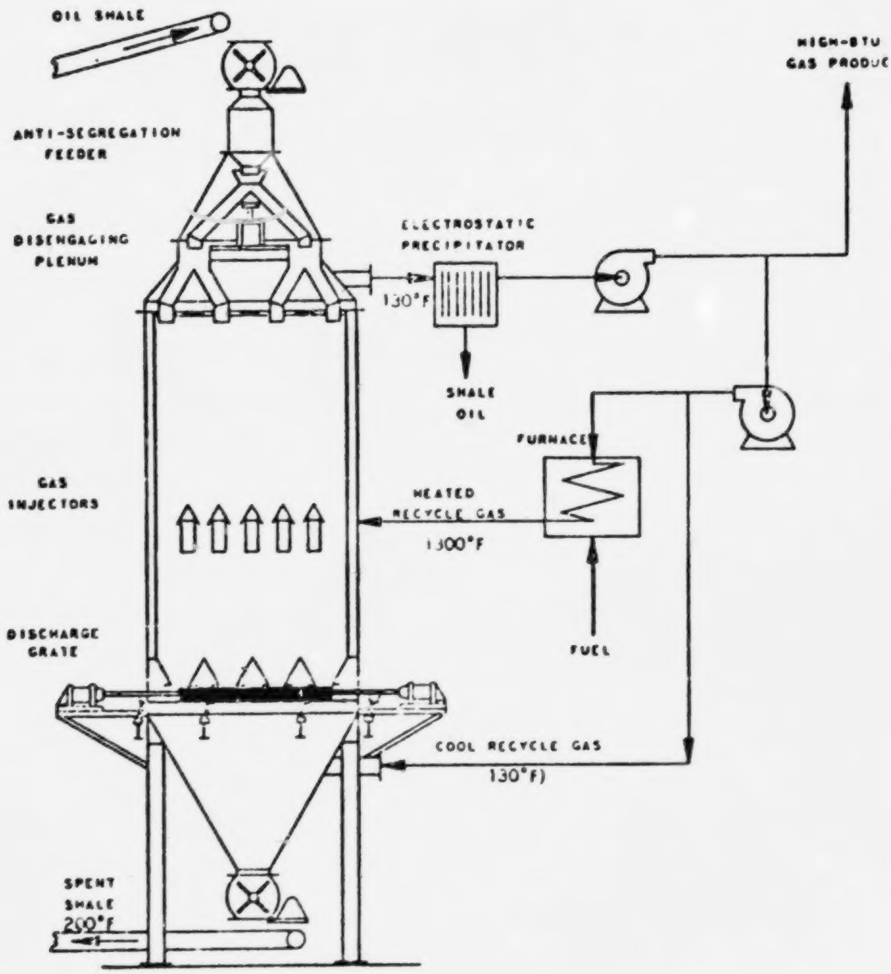
OIL SHALE
HIGH-BTU GAS PRODUCT
ANTI-SEGREGATION FEEDER
GAS DISENGAGING PLENUM
ELECTROSTATIC PRECIPITATOR
130°F
SHALE OIL
FURNACE
GAS INJECTORS
HEATED RECYCLE GAS
1300°F
DISCHARGE GRATE
FUEL
COOL RECYCLE GAS
130°F)
SPENT SHALE
200°F

FIGURE 11. PETROSIX PROCESS(18)

Crushed shale enters an anti-segregation feeder: a rotating "pants-leg" chute which discharges the shale into an annular stationary trough. Tubes in the trough distribute the shale to different locations at the top of the kiln. The crushed shale moves downward through the product cooling zone, the retorting zone, and a heat recovery zone. Combustion air is not admitted to the kiln, so no heat is generated internally. Instead, part of the recycle gas is heated in an external furnace to 705 C and is injected into the retort at its midpoint. Additional cold recycle gas, at 54 C (130 F), is introduced at the bottom of the retort, where it rises through the shale-bed recovering heat from the hot spent shale. This gas then mixes with the injected gases to heat and retort the shale in the upper part of the vessel. The oil and gas are carried out of the retort as a mist and are collected and separated. Product gas from the Petrosix process is undiluted with combustion gases, and, therefore, has a relatively high heating value and may be readily processed for recovery of sulfur, ammonia, and condensable hydrocarbons. The spent shale enters a discharge grate which has annual openings. A number of hydraulic cylinders, spaced around the circumference of the kiln, move the grate in a circular path to insure a uniform flow of spent shale out of the kiln.(1)

Status of Development

Published details of Petrosix process development are scant; however, it is known that a 900-1400 kkg/day semiworks plant is operating in Brazil.(19) In addition, a 2267 kkg/day kiln is now being constructed in Brazil for use in the Petrosix process. Kilns with 5.5 meters* diameter are already in existence in other than oil shale retorting processes. Kilns of 10.7-13.7 m diameters are considered by Cameron Engineers to be operable for use with oil shale.(1) When the 2267 kkg/day (2500 ton/day) facility is completed, it will be the largest existing shale retorting facility. Considering 9,000 kkg/day to be the minimum desired capacity for a single unit of a multiple retort commercial facility, this new Petrosix process facility will be one-fourth commercial scale. Petrosix data on yields of oil from U.S. raw shale are not available; however, since Brazilian oil shales average a much higher oil assay than U.S. shales, a lower yield process could still be economically viable when using the oil-rich Brazilian shales.

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* 1 meter = 3.3 feet approximately.

Nature of Products

The characteristics of the oil, gas, and spent shale produced from U.S. oil shale by the Petrosix process are not available. However, expected product characteristics are presented as follows.

Oil. The oil produced in this retorting process should be similar to the oil produced from other vertical retort processes such as the gas combustion and Union Oil processes. Typical analyses of these oils have been presented in the previous sections.

Gas. Gaseous products from the Petrosix process should be superior to that produced by direct fired internal combustion retorting processes (i.e., gas combustion and Union Oil). Typical analyses of gases produced from an externally heated retorting process (TOSCO process) are presented in the following section. Expected heating value is high (6300-7200 kcal/scm*) and approaches pipeline quality gas Btu rating. Because the gases are not diluted by nitrogen, the high sulfur and hydrogen content of the gas can be economically exploited. A low nitrogen, low sulfur, relatively high Btu gas that can be utilized in a variety of on-site and off-site uses is possible. A remote possibility that the gases might be piped through existing natural gas supply lines for sale also exists.

Spent Shale. Because the Petrosix process involves a vertical bed arrangement, the minimum particle size of the oil shale feed is limited. Therefore, like other vertical processes, the resulting retorted shale would be expected to retain its approximate initial size. The loss of shale by the entrainment of fines in the gas stream should be relatively low because of the large shale rock size distribution employed. The residual carbon content of spent shale is expected to be high due to absence of direct fired internal combustion heating.

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* 700-800 Btu/scf.

Process Efficiency

Thermal Efficiency. Again, available data to accurately evaluate the efficiency of this retorting process is inadequate. The use of an externally heated heat transfer fluid is a less efficient means of retorting the shale than internal direct heating as regards thermal efficiency. However, with this type of heating,dilution of the product gas is avoided. The result is a trade-off. A smaller quantity of a more easily handled high Btu product gas is produced but the retorting process requires a greater heat input. Combustion of the carbonaceous matter left on the retorted shale, as a means of generating this additional heat, is a definite possibility although it is not mentioned in the literature as part of this process. Additional data are needed to evaluate this process.

Product Yield. Data are not available on the yields of crude shale oil from oil shale.

Costs. The Petrosix process is slightly more involved than the two previously discussed retorting processes. The inclusion of the recycle gas furnace in the process train will add to required capital investment. The economics of the trade-off between the additional equipment and producing a gas amenable to the recovery of sulfur, ammonia, and condensable hydrocarbons, and the additional capital for the recovery operations versus the value of the recovered products, is unknown. However, it is believed(20) that this process is more advanced and, therefore, has better chance for economic success.

The capital cost for retorting, employing the Petrosix process, has been estimated at $1108 per kkg of retort capacity. This cost is expected to apply to the general range of plant capacity up to 63,000 bbl/day. Estimated retort operating costs (not including interest on capital, taxes, insurance, cost, or land and working capital) are $1.26/kkg ($1.14/ton) of shale retorted. All costs were escalated from 1968 costs to late 1973 by the Chemical Engineering Plant Cost Index.(18)

Process water requirements are not directly addressed in the literature for the Petrosix process. Possibly the recycle gas furnace could require noncontact cooling of certain vital parts; this would require a relatively high quality (river) water, of which a certain quantity would be lost upon cooling and a certain quantity would have to be bled. The required quantity of water in the semiarid area of U.S. oil shale deposits could become a very significant factor in the overall profitability of the Petrosix process.

The retorted shale produced will require disposal. The increase in specific volume of this shale is, therefore, critically important. The spent shale from the Petrosix process is expected to have a disposal problem of a smaller magnitude than the two previously discussed processes because the oil shale is simply pyrolyzed rather than combusted and pyrolyzed. However, if the carbonaceous matter retained on the spent oil shale is burned to recover its heat content, a finely divided shale ash would be produced. Such shale ash often has an increase in specific volume as high as 60 percent rather than the more typical 30-50 percent. In addition, the quantity of water required in adequate landfilling of this material is much more than for larger sized spent shales. Whether the economic advantages possible through the recovery of heat from the pyrolyzed shale would outweigh the economic penalties is not known.

Environmental Considerations

Preretorting

Preretorting. The pollution aspects of the Petrosix process from the preretorting operations (i.e., crushing, grinding, and sizing of the oil shale) are identical to the two previously discussed vertical kiln configuration processes. The larger particle size of the shale feed decreases the potential for air pollution while creating a potential solid waste (undersized oil shale) and lowering the utilization of all the mined shale. These problems can be effectively dealt with by installing an auxiliary briquetting operation.

Retorting. The retorting operation will produce a gaseous product stream containing the shale oil and product gases and a spent shale stream. The collection and separation of the valuable products in the gaseous stream can be adequately controlled since both the oil and product gases will need further processing. The product gases can be piped to gas desulfurization units. Since the fuel will have been desulfurized, the gas furnace can be equipped with readily available particulate removal systems. The spent shale leaving the retort will be relatively hot (94 C;200 F). Therefore, like the previously mentioned processes, adequate precautions will have to be taken to minimize emissions. Alternately, if the spent shale is employed for heat generation by combustion of the carboneous matter retained on it, additional pollution abatement would be required.

Expected Commercial Development

The very advanced stage of process development makes the Petrosix process among the leaders in the commercial exploitation of the vast oil shale resources. Development plant scale-up of only 4 times would be required to obtain a commercial unit. In addition, this process shows promise because it combines the very extensive research of the Bureau of Mines process with a process modification which produces a more useful, higher Btu, undiluted product gas.

The Brazilian government is expected to help subsidize the development of this retorting process. In the United States, the development of the gas combustion process could be extended to include this modification of the heating procedure.

TOSCO Process (Type 4)

Process Description

The Colony Development Operation's TOSCO II retorting process is characterized by: (1) the use of a horizontal rotating kiln, wherein shale is agitated and transfered through the retorting zone by the mechanical rotation of the tilted kiln, (2) direct solids-to-solids heat transfer, and (3) heat supply by externally heated ceramic balls. The essentials of the process are illustrated in Figure 12. Crushed shale (-1.3 cm size) is preheated and pneumatically conveyed through a vertical pipe to the retort by flue gases from the ball heating furnace.The preheated shale then enters the horizontal pyrolysis drum along with previously heated (650° C) ceramic,heat-carrying balls.(20) The shale is brought to a retorting temperature of 480° C (900° F) by conductive and radiant heat exchange with the balls. The oil vapors and gases are removed from the drum, cooled, and the oil and gases separated and sent to further processing. The drum is discharged over a trommel screen where the balls are separated and recycled back to the ball heater. Combustion of up to 5 percent organic carbon retained on the retorted shale, or alternately a fraction of the retort gas, will provide the required energy for the reheating of the balls; the flue gas generated is further utilized, as noted, for preheating the incoming shale. The finely divided spent shale or shale ash (when employed for a fuel) is then cooled and sent to disposal.(1,5)

Status of Development

The TOSCO II process has its origin in the "Aspeco" process-the rights to which were purchased from Aspegren & Company of Stockholm, Sweden,in 1952. The Oil Shale Corporation was formed to exploit this process and, in 1955, contracted with the Denver Research Institute (DRI), University of Denver, to conduct engineering research and development. DRI constructed both a 136 kg/hr laboratory unit and a 22 kkg/day pilot plant and operated these for TOSCO for several years. In 1964, the Colony Development Company was formed to

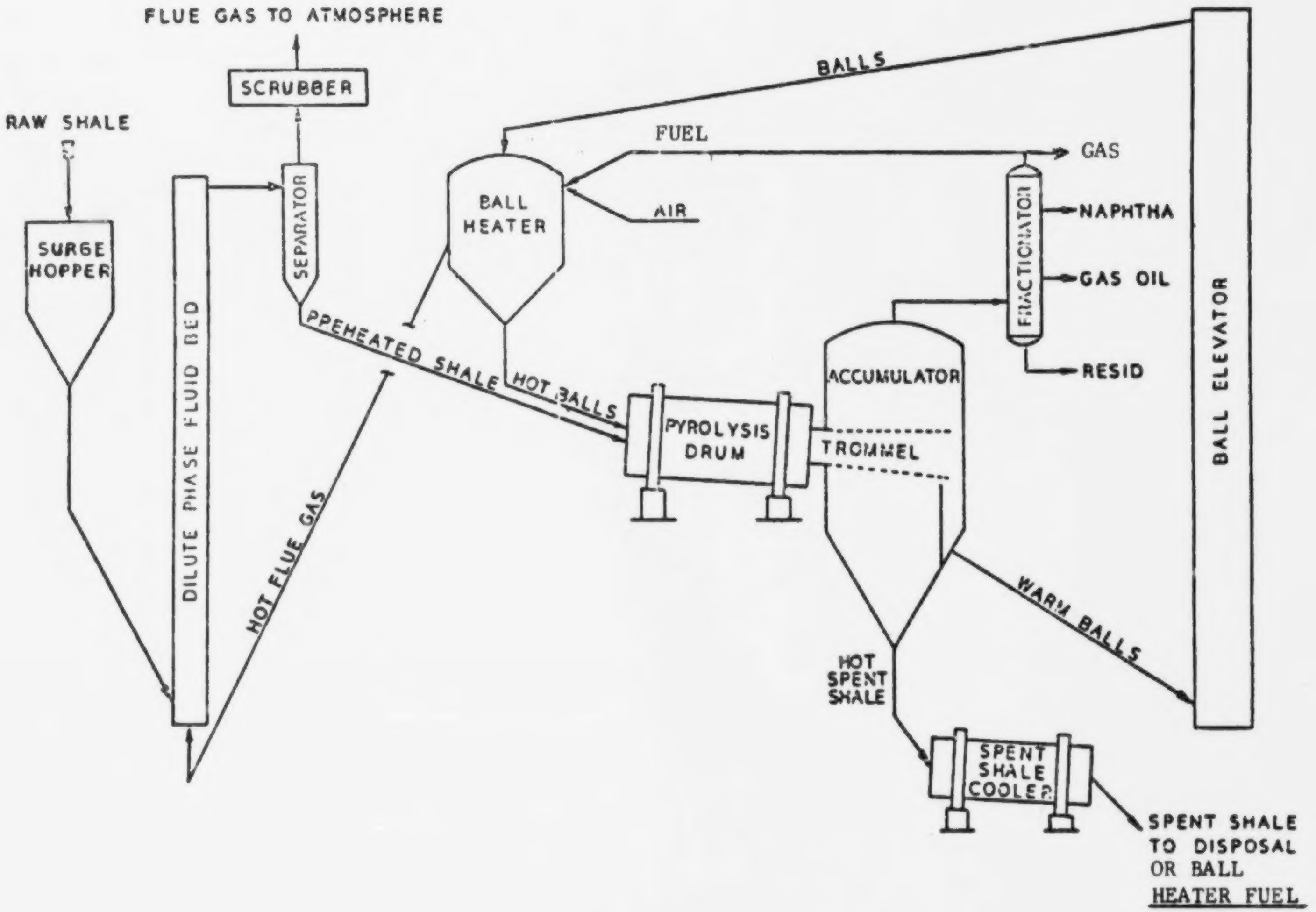
FLUE GAS TO ATMOSPHERE
SCRUBBER
RAW SHALE
SURGE HOPPER
DILUTE PHASE FLUID BED
SEPARATOR
HOT FLUE GAS
PPEHEATED SHALE
BALLS
FUEL
BALL HEATER
AIR
HOT BALLS
GAS
FRACTIONATOR
NAPHTHA
GAS OIL
RESID
PYROLYSIS DRUM
TROMMEL
ACCUMULATOR
BALL ELEVATOR
WARM BALLS
HOT SPENT SHALE
SPENT SHALE COOLER
SPENT SHALE TO DISPOSAL OR BALL HEATER FUEL

FIGURE 12. TOSCO II PROCESS(5)

commercialize the TOSCO II process. Participants in this venture were The Oil Shale Corporation, Standard Oil Company (Ohio), and Cleveland-Cliffs Iron Company. This group financed the construction in 1965 of a 900 kkg/day semi-works plant located on Parachute Creek, near Grand Valley, Colorado. The plant was operated by the group until September 1966, when The Oil Shale Corporation assumed sole responsibility until they placed the unit on stand-by in 1967. Atlantic Richfield Company joined the group, now Colony Development Operation,in 1969 and has since been responsible for modifying and reactivating the semi-works plant. Operation was begun again early in 1971(1) and completed in late 1972.(14) Ashland Oil is the latest to join in the TOSCO recovery process. Atlantic Richfield, The Oil Shale Corporation,and Ashland Oil now hope to start building a 50,000 bbl/day plant in the Piceance Basin of western Colorado during 1974, with construction to take about three years. Sohio and Cleveland-Cliffs hold an interest in the privately owned oil-shale reserves that are likely to be selected for the plant site, and retain the right to join in construction of the facility.(1)

Nature of Products

Oil. The yield of oil from the demonstration scale unit (900 kkg/day size) has been termed "excellent".(5) Various sources have reported yields as high as 105 weight percent of Fischer assay.(1) Properties of the crude shale oil are displayed in Table 8 .

TABLE 8. PROPERTIES OF CRUDE SHALE OIL PRODUCED BY THE TOSCO II PROCESS(5)

Gravity, API	28.0
Sulfur, wt %	0.80
Nitrogen, wt %	1.70
Pour Point, C (F)	23 (75)
Viscosity, centistoke @ 38 C (SUS @ 100 F)	25.4 (120)

Gas. The retort gas produced by the TOSCO II process is undiluted by combustion gases. In addition the use of a lower retorting temperature limits the dilution of the product gas by CO_2 released from the high temperature decomposition of inorganic carbonates in the oil shale. Characteristics and yields of untreated and desulfurized retort gases typical of indirectly heated retorting processes are presented in Table 9.

TABLE 9. PROPERTIES OF RETORT GAS PRODUCED BY INDIRECT HEATED RETORTING PROCESSES(5)

	As Produced	After Desulfurization
Composition (Volume %)		
Nitrogen	0	0
Carbon monoxide	4.0	4.2
Carbon dioxide	23.6	24.8
Hydrogen sulfide	4.7	(0.02)
Hydrogen	24.8	26.0
Hydrocarbons	42.9	45.0
Gross Heating Value		
kcal/scm	6975	7335
Btu/scf	775	815
Molecular Weight	25	24.7
Yield, scm/bbl oil (scf/bbl oil)	25.8 (923)	24.6 (880)

Spent Shale. Spent shale or shale ash (depending on the use of the retorted shale) from the TOSCO II process is very finely divided, with particles in the sand-to-clay size range. Disposal of such fine material will require special care because of the inherent dust problem. In addition, a greater quantity of water will be required to moisten spent shale before transportation and disposal.

Process Efficiency

Thermal Efficiency. The transfer of heat to the shale by externally heated materials is normally a far less efficient process than direct heat transfer by internal combustion. However, because of several offsetting advantages resulting from this retorting method, better overall shale oil extraction is accomplished. The exclusion of combustion products, mainly nitrogen, allows the production of an undiluted retort gas. In addition ,the heat required to raise the temperature of the incoming combustion air is conserved. Another advantage of this mode of retort heating is the minimal decomposition of inorganic carbonates in the shale resulting from greater shale agitation and hence controlled temperature retorting. Limiting thermal decomposition reactions results in additional heat savings.

Product Yield. The yield of shale oil from raw oil-shale by the TOSCO II process is the highest of any reported process. Yields as high as 104-105 percent of Fischer assay are reported with the demonstration scale unit and a yield of 100 percent is assumed appropriate for a commercial scale facility.(1)

If the carbonaceous residue on the retorted shale can be effectively utilized to provide the heat for the ball heating operation - thereby allowing the total gas production to be included in the yield from the process, then yields as high as 126 percent of Fischer assay are possible.(1) The use of the rotary kiln rather than a vertical bed eliminates the lower particle size restrictions; in fact,it requires a higher degree of crushing and size reduction than any other process.

Costs. The very high yields possible with the TOSCO II process will allow the construction of a commercial scale facility of lesser capacity equipment than the Type 2 or 3 retorting processes. As with the Petrosix process ,the retort gas will be undiluted with combustion gases and easily lends itself to desulfurization,resulting in the production of sulfur, ammonia, and condensable hydrocarbons. The very high carbon content of the spent shale makes this product an excellent auxiliary fuel for the reheating of the retorting balls ,thus freeing the retort gas for the operation of the post-retorting facilities. The capability of the process to accept shale fines results in complete shale utilization. However, the requirements for finer crushed input shale will result in higher preretorting costs and possibly the necessity for additional air pollution control equipment. No water is required for the retorting operation, but significant quantities will be required for the ultimate disposal of the spent shale. Because the kerogen is so completely extracted in this process the residue has little structural stability,(2) resulting in an increase in specific volume as high as 60 percent. The increase in specific volume will necessitate the disposal of a majority of the spent shale in landfills since only a fraction can be replaced in the shale mines. This represents an additional cost factor.

Data on cost estimates of commercial scale retorting operations are scant. Assuming that the TOSCO II process is employed and retort gas is not needed for retort plant fuel, because the process is assumed to utilize heat recovered from burning the coke-like deposits on the spent shale, estimates of capital and operating costs follow.*

The capital cost for retorting is estimated at \$1820 per kkg (\$1650 per ton) of retort capacity. This cost is expected to apply to the general range of plant capacity of 54,400-72,600 kkg/calendar day (60,000 to 80,000 tons/calendar day) production of 53,000 to 71,000 bbl/calendar day of oil from 37.1 gal/ton oil shale. Included in the above costs, in addition to the complete retorting system, are costs for site preparation, tankage and other off-site construction, buildings, sewer system, gas compression and absorption plant, oil and gas pipelines to the up-grading plant, and 25 percent contingency in the entire plant. An estimated paid-up royalty cost is also included.(1)

Estimated retort operating costs (not including depreciation and income taxes) are \$0.41/kkg (\$0.37/ton) of shale retorted during the first 15 years and \$0.52/kkg (\$0.47/ton) during subsequent years. The additional cost for later years provides for increased maintenance.(1)

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* Based on June, 1970, costs and escalated to December, 1973, using CE plant cost index (CPI). The escalation is 16% for the 3-1/2 year period.

Environmental Considerations

Preretorting. The main influence of the TOSCO II process on environmental emissions from the preretorting facilities will be because of the very fine particle size requirement. Shale feed must be crushed to 1.3 cm (0.5 in.) or smaller size for efficient oil extraction. This results in large quantities of fines and necessitates the use of efficient dust control devices. A positive aspect of this finer size requirement is that all the shale received can be utilized without creating a raw shale fines disposal problem.

Retorting. The undiluted gaseous stream produced by the retorting operation will contain the shale oil and the retort gas. Both components, as process products, can be adequately collected and separated with minimal environmental emissions. Both streams will be transferred to adjacent processing facilities for refining, separation, and/or purification. (These will be briefly discussed as part of the pollution aspects of the post-retorting processes).

Spent shale with a high degree of carbonaceous residue can either be disposed of directly or more efficiently burned in the process to liberate heat for the reheating of the retorting balls. The cleaning of the resultant flue gas will be a necessary, requiring cyclones, baghouses, or electrostatic precipitators. The removal of the sulfur from these gases will also be necessary. Employing the shale residue for fuel will probably require conventional stack gas cleaning--such as scrubbing--which could become expensive because of the scarcity of water.

Post-Retorting. No special pollution problems are anticipated in the shale-oil refining operation as a direct result of special process requirement of products produced by the TOSCO II process. The separation and purification of the retort gas however will most likely result in the need for additional pollution abatement equipment. Since these operations are currently being performed on a large scale at most U.S. refineries with adequate pollution controls sufficient technology should exist to assure that the environment can be protected during retort gas purification.

Expected Commercial Development

The TOSCO process is currently the most likely candidate process to be developed commercially. Predictions on the imminent initiation of construction of a 50,000 bbl/day facility have been announced as early as 1968.(14) A most recent announcement was to the effect that construction on a 50,000 bbl/day plant will begin in 1974.(15)

The TOSCO II process has been extensively demonstrated over a period of years in a 900 kkg/day facility. It is believed that sufficient engineering data have been generated to scale up the demonstration facility to commercial scale.

As the most advanced retorting process which has been demonstrated on a large scale, the TOSCO II process would be expected to be eligible for new federal energy monies for the development of commercial-scale retorting technology. Actual development of the planned 50,000 bbl/day plant would certainly enhance this position. The Colony Development Operation is a diversified group of private industries pooling their resources to commercialize the TOSCO II process. Included in the group are the developers of the TOSCO II process, three oil concerns and a mining company. Collectively they represent sufficient capital and technology to commercially develop the TOSCO II oil shale retorting process.

VI. RETORTED SHALE REFUSE DISPOSAL

The spent shale and shale ash produced by the various ex-situ retorting processes are expected to be a large percentage (up to 70 percent) of the shale input on a weight basis. On a volume basis, the expected quantity of refuse will be even larger due to swelling. This chapter reviews the magnitude of this disposal problem and possible disposal methods. In addition, the spent shale characteristics will be reviewed to determine the potential for its economic use.

Factors Affecting the Magnitude of the Disposal Problem

The various retorting techniques will have differing effects on the quantity and physical and chemical characteristics of the spent shale produced. The differences in certain important physical properties of spent shale from three different processes are shown in Table 10. Four parameters of the magnitude of the disposal problem can be identified. They are: (1) yield--the percent extraction of shale oil from the raw oil shale; (2) specific volume--the degree of increase in the volume of the shale feed after retorting; (3) compactability--the reduction in volume resulting through natural or artificially induced settling of disposed shale; and (4) leachability--the susceptibility of chemical ions in the retorted shale to enter into solution with water percolating through or flowing over retorted shale.

Yield

The efficiency of the retorting process in terms of the quantity of shale oil recovered from the raw oil shale will dictate the tonnage of feed that will require processing to obtain a desired production capacity. The exact yields obtainable by any of the retorting processes in a commercial scale facility are unknown since no process has been commercialized. However, by noting the performance of the demonstration scale facilities approximate estimates can be obtained. The gas combustion retorting process of USBM has

TABLE 10. PHYSICAL PROPERTIES OF RETORTED SHALE (5)

Property	Retorting Method Gas Combustion	Union	TOSCO II
Geometric mean size, cm (in)	0.205 (0.081)	Not Reported	0.007 0.003
Permeability - cm^2 (in^2)	3.46×10^{-9} (5.36×10^{-10})	Not Reported	2.5×10^{-10} (3.88×10^{-11})
Bulk density, g/cc (lb/ft^3)	1.44 (89.90)	1.80 (112.37)	1.30 (81.16)
Solid density, g/cc (lb/ft^3)	2.46 (153.58)	2.71 (169.19)	2.49 (155.45)
Maximum size, cm (in)	3.81 (1.50)	Not Reported	0.476 (0.19)
Minimum size, cm (in)	0.00077 0.0003	Not Reported	0.00077 0.0003

shown decreasing oil yield as the capacity of the processing facility is increased, e.g., 94-95 percent at 5.4 kkg/day and 83-87 percent at 136 kkg/day(4) and about 85 percent at 272 kkg/day.(14) These yields, when extrapolated to a commercial scale of 10,000 tons per day per unit, reduce to 78 percent. At this yield 22 percent additional shale would have to be processed over a system capable of a 100 percent yield, such as the Colony Development Operation's TOSCO II retorting process. Yield for this latter system ranges from 104 to 126 percent of Fischer assay at the 900 kkg/day capacity level and is conservatively estimated at 100 percent for commercial scale.(1) No data to estimate possible commercial scale yields with either the Union Oil or Petrosix process have been reported. The Union Oil retort was capable of over 100 percent yield at the 1.8 kkg/day scale.(16) Generally both processes are considered very efficient and an average industry estimated yield is 86-95 volume percent.(5) Assuming these estimates to be accurate indications of the variation of oil yields as a function of the retorting process, the variation in refuse produced could be as high as 30 percent.

Specific Volume

The volume of shale refuse to be disposed of is directly proportional to the "swelling" of the shale feed. The organic material (kerogen) present in the raw shale seems to be the cementing agent that holds the rock together so that extraction of the organic material leaves a residue with little structural stability.(14) Therefore, the more complete the extraction process, the lower the structural stability, and the more friable or brittle the retorted shale becomes. The resulting swelling problem therefore is accentuated by extensive initial crushing and agitation during the retorting process. Both crushing and agitation tend to increase the extraction of oil(4) and tend to produce a greater quantity of smaller end products.

The gas combustion, Union Oil, and Petrosix processes all employ a vertical kiln retorting arrangement, necessitating the use of rather large sized feed shale particles and producing similar sized spent shale. In addition, all three processes extract considerably less than 100 percent of the organic matter in the raw shale. Therefore, the increase in specific volume of the spent shale above that of the feed from these three retorting processes should be relatively low. However, the volume of spent shale from any known retorting process, even after maximum compaction, is at least 12 percent greater than its in-place volume.(5) Reported data show that typical shale ash from the Union Oil process increased approximately 21-28 percent in specific volume after retorting.(1) Similar increases in specific volume could be expected with the gas combustion or Petrosix processes. The TOSCO II retorting process, as noted in the previous section, employs (1) a much smaller feed size than any of the other three processes, (2) a rotating rather than a stationary extraction process which tends to grind or fracture the embrittled shale, and (3) obtains a 100 percent or greater oil yield. All three factors tend to increase the specific volume of the sand-sized spent shale. Specific volume increases as high as 60 percent are reported for the TOSCO II process.(1)

The above data indicate that an average increase in volume of loosely dumped spent shale over in-place shale can be at least 50 volume percent.

Compactability

The degree to which retorted shale can be compacted either by natural cementation or external pressure directly affects the volume of disposal area required. Two characteristics can be identified which are important to the compactability of spent shale. They are: (1) surface carbon content and (2) particle size distribution. Small scale experimental work indicates that natural surface-cementation reactions are inhibited if a material amount of carbon is present to coat the particles.(5) The particle size distribution is important because large void spaces will exist in shale dumps composed of large shale rock. These void spaces tend to limit natural cementation and resist mechanical compaction.

The Union Oil retort produces a completely burned shale ash which may contain large chunks of clinkered material, but most of the ash is about the same size range as the feed, 0.3 to 15 centimeters, with a relatively small amount of fines. The larger materials may require crushing prior to the water addition and compaction. The lack of carbon should approximately offset the larger spent shale size to produce an average compactable refuse.

The gas combustion process spent shale is considered intermediate with about 3 percent carbon content. This is a high enough carbon content to inhibit some surface cementation reaction. In addition, the relatively large spent shale particle size should somewhat inhibit natural and artificially induced compaction.

The Petrosix process, which establishes heat transfer through the use of an externally heated carrier fluid, produces a high carbon spent shale ranging from 5 to 6 percent organic carbon. Like the gas combustion process, this is certainly enough carbon to limit certain natural cementation reactions. The Petrosix process also produces a relatively large sized spent shale which will somewhat inhibit compaction efforts.

The TOSCO II process products (like the Petrosix process) have a high carbon refuse. However, the particle sizes of the spent shale is of the sand grain size--which should offset the negative cementing characteristics of the TOSCO spent shale. The average compaction of loosely dumped spent shale is assumed to result in a 25-26 percent volume reduction; this, however, is still a 13-16 percent increase in volume over the in-place oil shale. This can be interpreted as only requiring 13-16 percent of the spent shale to be eventually disposed of above ground--the rest being returned to the worked out mine. Less optimistic forecasts of 40 percent above ground disposal are often considered more accurate. In any event, use of the worked out mine for a spent shale disposal site will require waiting for a considerable amount of time (up to 16 years) for completion of the commercial operation. Until that time 100 percent of all spent shale will have to be properly disposed of above ground. Table 11 displays the anticipated quantity of oil shale that would have to be mined and the annual volume of spent shale that would have to be disposed for various upgraded shale oil capacities.

Leachability

Another factor effecting the magnitude of shale refuse disposal problem is the leachability of spent oil shale. This will dictate the degree of water channeling required to redirect water around the disposal sites

TABLE 11 . QUANTITY OF IN-PLACE AND SPENT SHALES

Upgraded Shale Oil Production Plant Capacity (bbl/day)	Shale Mined, 10^6 kkg/yr (10^6 ton/yr)	Shale Volumes 100 Million cu.m./yr (Billion cu.ft./yr)		
		In-Place	Spent (loose)	Spent (Compacted)
50,000	24.4-27.1 (26.9-29.9)	0.11-0.13 (0.40-0.45)	0.17-0.20 (0.60-0.70)	0.13-0.15 (0.45-0.52)
100,000	48.8-54.2 (53.8-59.8)	0.22-0.25 (0.80-0.90)	0.34-0.39 (1.20-1.40)	0.25-0.29 (0.90-1.04)
250,000	122.0-135.6 (134.5-149.5)	0.56-0.63 (2.00-2.25)	0.84-0.98 (3.00-3.50)	0.63-0.73 (2.25-2.60)
1,000,000	488.0-542.4 (538.0-598.0)	2.24-2.52 (8.00-9.00)	3.36-3.92 (12.00-14.00)	2.52-2.91 (9.00-10.40)

Basis: Oil shale assaying 30 gallons per ton; upgraded oil yield of 86-95 vol. pct., based on in-place crude shale oil potential; loosely dumped spent shale bulk density of 71-75 lbs. per cu. ft.; compacted spent shale bulk density of 90-100 lbs. per cu. ft.

and the number and size of retaining ponds required to collect water which has flowed over or percolated through the shale dump. Three factors can be identified which are important to the susceptibility of spent shale leaching. They are (1) refuse compaction, (2) carbon content, and (3) carbonate decomposition. The factors which inhibit refuse compaction have been discussed in the preceding paragraphs. The carbon content of retorted shale was also discussed in its inhibiting effect on natural surface cementation. However, the carbon coating on the spent shale also has the effect of preventing water penetration to the extent that percolation-type leaching is not expected to be a problem.(21)

Methods of Disposal of Retorted Shale Refuse

The cooled and moistened solid residue from retorting will be disposed of by a system involving minimum handling, such as truck or belt transport, to convey the waste material to adjacent canyons or other topographic depressions. Disposed material will be compacted, as needed, to maintain stability as the pile is built up. To prevent downstream pollution by dissolution of soluble material from the residue during run-off periods, disposal areas must be adequately safe-guarded by dams, culverts, and/or diversion ditches.

Disposal of fine-sized residue by slurrying and pumping to a disposal pond has considerable attraction because of the relative simplicity and low cost of the system. However, such disposal may be limited by two factors: (1) inadequate disposal areas and (2) water availability. High dams will be required to impound adequately sized tailings ponds in topographically low areas. Since it appears that some residue may be too fine-grained to be safely used alone in the construction of such dams, other suitable material which is likely to be more expensive, since it may not be readily available, may be required. In addition, slurry disposal consumes a considerable amount of water due to evaporation and retention in the solid fill. Adequate water supplies undoubtedly will be a future problem and this may preclude disposal by the slurry method. It is possible that saline water, if produced from some deep mines, could be used and recycled, thus solving two disposal problems.

As a means of protecting the environment, all residue disposal areas will have to be adequately protected against erosion. Erosion would be of particular concern on the steep slopes of unprotected residue piles. Storms could lead to the formation of deep gullies on the slopes and alter the pattern of drainage established from preceding runoffs. Continued erosion also would expose new surface areas to air and moisture which could lead to undesirable leaching and the creation of water quality problems. The effect of revegetation on these potential problem areas is unknown. If unprotected, a large portion of the sediment from the spent shale piles might be deposited in stream channels near the disturbed area. However, sediment also would be carried into large streams, where it would settle out or move downstream. Thus, entire river basins could be adversely affected by the spent shale piles if no care was taken to prevent these potential problems. If streams are required to carry heavy loads of sediment, additional treatment may be required to make them more suitable for domestic and industrial uses. In addition, recreational use of streams could also be adversely affected by sediment, and fish habitat could be destroyed.

Erosion of spent shale piles may be lessened to some extent through physical, chemical, and vegetative methods of stabilization. Physical methods include covering the fine tailings with topsoil removed from underneath the shale residue piles. One possibility for a surface disposal site would be a canyon in the vicinity of a proposed commercial plant site. The processed shale could be placed in a series of horizontal layers 1 to 2 feet thick. The upper surface would be a temporary surface until the last layer is placed. Each layer could be started a little further back into the canyon, giving the front surface of the pile (permanent surface) a slope sufficiently less than the angle of repose to insure frictional stability. Chemical stabilization, involving reacting the residue with a reagent to form a water and air impermeable crust or layer, could also be employed. Vegetative stabilization may pose some difficult problems. Wastes are usually deficient in plant nutrients or may contain material noxious to plant growth. Tailings and other fine wastes usually must be covered to a depth of four inches or more with soil and fertilized prior to seeding.

However, Kentucky Blue Grass, fertilized at the rate of 150 pounds per acre twice per year and watered at the rate of 1 inch per week during the 10 week summer season has been grown on the TOSCO II process waste after conditioning with sawdust.

Much consideration has been given to the disposal of solid residue in mined-out areas underground. Ultimately this procedure may prove to be a partial solution to the disposal problem, because the decreased specific gravity of residue compared to the in-place rock restricts disposal in this manner to a maximum of about 70 percent (more likely 50 to 60 percent) of the total volume of waste material produced.

Both conveyor and slurry methods for underground disposal have been studied. Conveyors pose great distribution problems and undoubtedly will be very expensive to install and operate. Pipeline transportaion of slurry eases the underground distribution problem and is less expensive but, as in surface disposal operations, may consume large amounts of water in addition to requiring numerous and expensive dams to seal off mined-out areas. Also, since the residue may not drain well, additional problems of water recovery and stability of filled areas should be considered. Control of particle size is essential. Ideally, particle size should not exceed 60 mesh for transport through pipelines, and oversize may have to be reground or screened out and disposed of elsewhere. For effective drainage and compaction much of the -325 mesh slimes may have to be removed and disposed of in some surface ponded area. The total effect of all this damming, processing, and handling may well make underground slurry disposal economically unattractive.(1)

The susceptibility to water leaching is effectively limited by proper disposal site construction and compaction. Leaching tests show that while there is a definite potential for high concentrations of certain minerals in the runoff from spent shale residues, upon proper compaction the disposal piles become essentially impermeable to rainfall. Studies conclude that water contamination due to percolation type leaching will be negligible and that the main emphasis must be placed on surface runoff. To this extent it is concluded that the greatest concern of possible water pollution is not with the normal snow and/or rain that occurs throughout the year but with occasional flash floods that may deposit large quantities of rainfall in a relatively short period of time. To handle this water and runoff from adjacent plateaus which drain into the disposal canyons, it will be necessary to either channel the water away from the disposal sites or install large conducts in the bottom of the canyon under the spent shale dump which lead to retaining ponds immediately downstream. This water, including the brines, can then be impounded and eventually returned and reused in subsequent disposal operations.

Utilization of Spent Shale

Oil shale contains other potentially valuable components in addition to the organic material. The characteristics of retorted oil shale and some of its potential economic uses will be reviewed in this section.

Characteristics of Spent Oil Shale

Detailed chemical analyses of spent oil shale show that the main differences in spent shale produced by different retorting processes are in the organic carbon and undecomposed carbonate contents. Table 12 presents several analyses of the mineral composition of spent shale ash from the nine minable beds in the Mahogany zone on an oxide basis and on a raw shale basis. These analyses should be typical of retorted shale because the mineral matter in oil shale of the Mahogany zone of Colorado and Utah, where oil shale averages 146 l/kkg* is very consistent, and regardless of the extent of decomposition, the basic oxide forms of the minerals in retorted shale are similar.

Potential Economic Uses

The principle products expected to be recovered are (1) alumina from the dawsonite deposits and (2) soda ash from the nahcolite (a natural sodium bicarbonate). The recovery of alumina has received the greatest interest. The Oil Shale Corporation (TOSCO II), Wolf Ridge Minerals Corporation, and Kaiser

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* 35 gal/ton.

TABLE 12. MINERAL COMPOSITION OF MINABLE-BED SAMPLES FROM THE MAHOGANY ZONE, RIFLE, COLORADO(4)

		Bed designation[(a)]									Aver-age	Com-posite
		C	J	A	D	H	B	I	G	EF		
Ash content of raw shale	wt. pct.	70.70	63.01	67.73	69.56	68.03	66.80	60.17	62.15	59.64	65.31	65.68
Composition of ash:												
SiO_2	wt. pct.	46.41	35.12	42.63	45.86	42.51	46.01	39.18	39.71	41.93	42.15	42.71
Fe_2O_3	wt. pct.	4.36	3.67	3.91	4.24	4.05	4.78	4.35	4.53	4.82	4.30	4.56
Al_2O_3	wt. pct.	13.08	10.21	13.66	13.65	12.42	12.18	9.78	13.56	13.81	12.48	13.15
CaO	wt. pct.	20.34	33.90	20.63	20.17	23.66	20.41	29.26	25.50	20.44	23.81	23.27
MgO	wt. pct.	8.80	13.43	12.82	9.15	9.84	8.10	10.27	8.58	8.62	9.96	9.97
SO_3	wt. pct.	1.21	.85	.87	1.58	2.17	2.11	2.50	2.90	4.35	2.06	1.81
Na_2O	wt. pct.	3.00	1.65	3.12	2.35	3.73	3.92	2.42	3.85	3.96	3.11	3.09
K_2O	wt. pct.	2.91	2.11	2.35	3.03	2.43	1.73	2.19	2.05	1.81	2.29	2.33
Total	wt. pct.	100.11	100.94	99.99	100.03	100.81	99.27	99.95	100.68	99.74	100.16	100.92
Ash composition, raw-shale basis:												
SiO_2	wt. pct.	32.8	21.9	23.9	31.9	23.7	31.0	23.6	24.5	25.4	27.5	27.8
Fe_2O_3	wt. pct.	3.1	2.3	2.6	3.0	2.7	3.2	2.6	2.8	2.9	2.8	3.0
Al_2O_3	wt. pct.	9.2	6.4	9.2	9.5	8.4	8.2	5.9	8.4	8.2	8.2	8.6
CaO	wt. pct.	14.4	21.2	14.0	14.0	16.0	13.7	17.6	15.7	12.2	15.5	15.1
MgO	wt. pct.	6.2	8.4	8.7	6.4	6.6	5.5	6.2	5.3	5.1	6.5	6.5
SO_3	wt. pct.	.8	.5	.6	1.1	1.5	1.4	1.5	1.8	2.6	1.3	1.2
Na_2O_3	wt. pct.	2.1	1.0	2.1	1.6	2.5	2.6	1.5	2.4	2.4	2.0	2.0
K_2O	wt. pct.	2.1	1.3	1.6	2.1	1.6	1.2	1.3	1.3	1.1	1.5	1.5
Total	wt. pct.	70.7	63.0	67.7	69.6	68.0	66.8	60.2	62.2	59.6	65.3	65.7

Footnotes to Table 12.

(a) Nine minable beds in the Maghogany Zone.

Note: Spectrographic and chemical analyses indicated the presence of other elements in Colorado oil shale in maximum amounts (weight percent) as follows:

Arsenic	0.005	Lead	.09	Silver	.001
Barium	.03	Lithium	.05	Strontium	.08
Boron	.03	Manganese	.08	Tellurium	.7
Chromium	.007	Molybdenum	.001	Titanium	.06
Copper	.008	Phosphorus	.4	Vanadium	.06
Gold	.001	Selenium	.001	Zinc	.1

Aluminum & Chemical Corporation have all developed process for extracting the alumina in oil shale. These companies have not disclosed any details of their processes, but government researchers have been working on nitric acid-leach techniques in which the acid is recovered and reused.$^{(22)}$ Their work has shown that complete extraction of the alumina in the sample was obtained with a dilute acid leach. Their tentative conclusions are that recovery of soda ash and alumina is feasible and is compatible with retorting for oil.$^{(23)}$

Alkaline leach tests performed at different residence times, temperatures and concentrations of sodium hydroxide have shown that good recoveries of alumina with low silica contamination are obtainable at room temperature and low residence times with relatively dilute sodium hydroxide (NaOH) concentrations. Maximum alumina recoveries at these conditions were 95 percent of the acid soluble alumina (approximately half the alumina content of the shale). An attractive feature of the leaching was that the leached pulp and liquor did not become gelatinous nor did slimes develop, and the residue was easily washed.

Economics of a postulated mining, retorting and by-products recovery plant employing (1) including physical separation of nahcolite from the raw shale, (2) conversion of part of the nahcolite to soda ash, and (3) recovery of alumina via the caustic leach process have been reported. Based on a plant processing 27,210 kkg/day (30,000 ton/day) of oil shale containing 21 percent nahcolite, 12 percent dawsonite and 15 percent organic material, total capital costs have been estimated at $140 million (based on 1968 costs escalated to late 1973). Of this total $31 million is for the mine, $13 million for the retort, $63 million for the alumina plant, and $33 million for the nahcolite and soda ash plants. By-products from the plant includes 5714 kkg/day (6300 ton/day) of nahcolite separated after the crushing step, with 1596 kkg/day (1760 ton/day) converted to soda ash. Spent shale is crushed, leached, filtered, washed, precipitated with CO_2, thickened, washed and calcined to produce 907 kkg/day (1000 ton/day) of alumina. Three quarters of the gross revenue of over $64 million per year is derived from the sale of byproducts$^{(22)}$. Although these economics look favorable, sufficient markets for the nahcolite and soda ash are questionable and plans to incorporate such an alumina recovery process in the proposed 50,000 bbl/day facility to be constructed in 1974 has not been reported.

Acid mine drainage pollution control utilizing nahcolite directly or by way of soda ash from nahcolite is another possibility. The potential consumption could be in the range of 3.5-4.5 MM kkg/yr (4-5 MM tons/yr). Present control of this huge acid pollution problem is either by neutralization with dolomite or limestone, or is nonexistent. Such treatment while beneficial has the undesirable effect of adding large amounts of calcium and magnesium hardness to the effluent. The use of sodium carbonate would provide more efficient neutralization as well as the reduction in hardness.(22)

One other possible use for the spent shale is portland cement clinker. As a major product of Estonian (USSR) oil shale industry, portland cement clinker offers high strength and high resistance to frost. The production of this clinker requires burning the shale at about 1982 C (3600 F) in special furnaces to melt the inorganic constituents. Other uses are bitumen for road building,(24) fill material, raw material for brick manufacture, and glass making.(22)

VII. OTHER ENVIRONMENTAL CONSIDERATIONS

The impact of the various oil production processes on waste generation has been discussed in previous chapters. However, it is important to consider the impacts of oil-shale industry on land and landscape, general aesthetics and recreation, noise, vegetation, economic and social development, and water resources and quality. These areas of concern are reviewed briefly in this chapter.

Impact on Land and Landscape

An estimate of land requirements for surface mining, underground mining, and in-situ processing is presented in Table 13. As expected, surface mining land requirements are the highest. After 30 years of shale development, surface mining would require about twice the land needed for underground mining and 5 times that needed for in-situ processing. In conclusion, the reduced land requirement for in-situ processing and underground mining with ex-situ retorting favor their development and use. The cumulative land disturbed in 30 years does not seem excessive. It would not be wise, however, to make firm conclusions without further investigation of this aspect.

Impact on Vegetation

Projected vegetation impacts associated with construction and operation of surface facilities, mining activities, overburden removal, processed shale disposal, and development of utility corridors will vary considerably from tract to tract depending upon the development options considered. The physical characteristics of the individual tracts also will determine impacts. The impact on vegetation areas disturbed for 8 types of plant communities and for the three types of mining and processing is summarized in Table 14(8).

Existing vegetation essentially will be eliminated from all land surface allocated to surface facilities, overburden storage, stockpiling, and waste disposal. Mining activities and waste disposal associated

TABLE 13. LAND REQUIREMENTS[8] (ACRES)*

Requirements	Years			
	5	10	20	30
Surface Mining:				
Surface disposal:				
With restoration	2,400	2,700	3,300	3,400
Cumulative land disturbed	2,450	3,200	5,000	6,650
Surface disposal with backfill:				
With restoration	2,450	2,700	3,300	2,700
Cumulative land disturbed	2,450	3,200	4,300	4,600
Underground Mining:				
Surface disposal:				
With restoration	350	700	850	1,110
Cumulative land disturbed	350	700	1,450	2,210
Underground disposal (60%)				
Cumulative land disturbed	350	600	800	1,090
In situ: With restoration	300	775	775	775

* At a production rate of 50,000 bbl/day.

TABLE 14. VEGETATION IMPACT AREAS - UNDERGROUND MINE, SURFACE MINE, IN SITU(8)

Resource Extraction Method

Vegetation Disturbed, Acres

Underground Mine

Plant Communities	Facilities	Mine and Overburden	Process Shale		Utility Corridors	Totals	
			Surface	Backfill		Surface	Backfill
Loamy slopes Big sage, serviceberry, wheatgrass	49	5	186	74	60	300	188
Pinyon-juniper Pinyon, juniper, serviceberry, stipa	42	2	558	222	30	632	296
Rolling loam Sagebrush, wheatgrass	21	3	56	20	30	110	74
Deep loam Sagebrush, stipa	7	0	40	16	20	67	43
Mountain swale Wheatgrass, wildrye	14	0	60	24	20	94	58
Loamy breaks Bitterbrush, serviceberry	7	0	30	14	10	47	31
Rough broken land Serviceberry, primrose Indian ricegrass	0	0	930	370	30	960	400
Totals	140	10	1,860	740	200	2,210	1,090

Surface Mine

Plant Communities	Facilities	Mine	Overburden	Process Shale		Utility Corridors	Totals	
				Surface	Backfill		Surface	Backfill
Loamy slopes Big sage, serviceberry, wheatgrass	75	360	300	380	182	120	1,235	1,037
Pinyon-juniper Serviceberry, stipa	40	180	100	1,000	456	80	1,400	856
Rolling loam Sagebrush, wheatgrass	35	180	150	120	54	60	545	479
Deep loam Sagebrush, stipa	20	120	120	180	91	40	480	391
Mountain swale Wheatgrasses, wildrye	20	120	100	170	91	40	450	371
Loamy breaks Bitterbrush, serviceberry, Indian ricegrass	10	60	70	80	36	20	240	196
Rough broken land Serviceberry, primrose Indian ricegrass	0	180	140	1,940	910	40	2,300	1,270
Totals	200	1,200	980	3,870	1,820	400	6,650	4,600

In Situ

Plant Communities	Facilities	Drilling	Overburden	Processed Shale	Utility Corridors	Total
Loamy slopes big sage, serviceberry, stipa	18	300	0	0	200	518
Pinyon-juniper pinyon, juniper, serviceberry stipa	12	180	0	0	120	312
Rolling loam sagebrush, wheatgrass	9	150	0	0	90	249
Deep loam sagebrush, wheatgrass	4	100	0	0	60	164
Mountain swale wheatgrass, wildrye	5	100	0	0	50	155
Loamy breaks bitterbrush, serviceberry, Indian ricegrass	2	50	0	0	30	82
Rough broken land serviceberry, primrose, Indian ricegrass	0	0	0	0	50	50
Totals	50	880	0	0	600	1,530

with underground mines will destroy the vegetation on small areas around the mine openings.

Vegetation changes will take place on the entire surface area involved in in-situ shale oil extraction activities. Existing vegetation will be eliminated from drill pad sites and the vegetation on the areas between drill pads will be damaged by trampling and mobile equipment operations.

Utility corridor development will completely remove existing vegetation from portions of the corridor and much of the balance of the corridor areas will experience substantial trampling impact from mechanical activities.

Revegetation is called for on portions of these areas when backfilling and surface placement of overburden has progressed to a point where workable areas are available for rehabilitation and when construction is complete in utility corridors and operations have progressed through in-situ areas that have been developed.

The existing vegetative complexes of these areas have evolved over long periods of time. The species and species groups are interdependent and in a reasonable degree of natural balance and stability. The natural balance between species and groups of species will be altered in some processing options (for example, in-situ processing) or completely destroyed in others, such as mine development and processed shale disposal areas.

In general, revegetation can be initiated on such disturbed areas as soon as activity is terminated. The nature of the resulting new plant communities and the pattern of the ensuing successional changes will also vary distinctly from site to site depending upon site characteristics, types of disturbance, species planted, revegetation methods, and subsequent management.

A considerable body of information is available on revegetating native soils.(5) Relatively successful cover establishment can be anticipated on disturbed native soils in areas such as utility corridors, and roadside cuts. Information on revegetation of processed shale and deeply disturbed parent soil materials is rather limited, research having emphasized grasses with only limited attention having been given to forbs and almost no long-term studies on shrubs. Thus, the optimum selection of species, germination and survival rate, and expected density of cover have not yet been fully established nor can the future pattern of succession be predicted with certainty.

If mixtures of native species, which include the major climax (or desired sub-climax) species, are used to revegetate disturbed native soils, natural progression may be relatively rapid. The planting of older age class shrub and tree seedlings could accelerate the establishment of more stable plant communities.

If exotic species are used, particularly as monocultures, successful changes will be much more extensive as the introduced species will eventually be replaced by natives beginning with aggressive invader species and ending with climax or "use sub-climax" species. Exotic plant monocultures can survive for extended periods with adequate management. However, they are susceptible to severe set-back by adverse climatic conditions and insect or disease infections, destroying the cover and increasing erosion. Maintenance of non-native species would therefore require long-term management.

Establishment of initial cover and successional change on processed shale disposal sites will be constrained by the plant growth media, and the semi-arid climate, exposure, slope, and cultural practices, including temporary irrigation and fertilization. Revegetated processed shale areas will be fragile sites highly susceptible to damage from biotic influences such as improper grazing or fire.

Impacts on Grazing

Development of an oil shale operation would affect grazing by removing land from grazing use, by disrupting livestock travel routes, and possibly by loss of watering facilities, but the impact would only be minor. Only the land actually occupied by the mining operations, the processing plant, waste disposal and related facilities would be removed from grazing use. Thus the extent of grazing loss would depend upon the mining method used and the rates and success of the rehabilitation measures.

The approximate reduction in grazing use of land that would be expected from 50,000 barrels per day of shale oil production operation for various mining and/or processing options is shown in Table 15.

TABLE 15. ACREAGE REDUCTION FOR GRAZING

Operation	Total Acres Affected	Average Grazing Area Loss Acres/yr.	Average Grazing Loss AUM/yr[a]	30-yr Accumulative Total AUM Loss
Open Pit	6,650	3,000	353	10,590
Open Pit (w/backfill)	4,600	2,800	329	9,880
Underground	2,210	1,100	129	3,880
In situ	1,510	720	88	2,650

(a) The animal unit months (AUM) of grazing loss figures are based upon an average carrying capacity of 8.5 acres/AUM for Track C-a and 7.9 acres/AUM for Track C-b.

Noise Impacts

During the initial exploration and construction phases on any of the selected tracts, the noise resulting from diesel trucks, compressors, mixers, drills, and other general construction machinery and vehicles might cause certain wildlife on or near the tract to move to other locations.

Once commercial-level operations are attained at each tract, it can be expected that the general noise level on each tract would increase over that associated with construction. Conventional surface mining would require power shovels, earthmovers, conveyors, and grinders that would generate considerable noise on or near the tracts. Similar problems, but with less intensity, would occur with underground mining techniques. Blasting, perhaps three times per day per operation, would create a routine disturbance and annoyance to the few local ranchers and wildlife. Retorting and upgrading processes would emit noises quite similar to those for petroleum refinery operations, although the level of such noise would depend on the specific processes employed. For the in-situ extractive processes, underground blasting, compressors, pumps, etc., would provide obvious noise sources.

General Esthetics and Recreation

Presently the area where the Green River oil shale deposits occur is remote and sparsely used by hunters and ranchers as well as oil and gas industry personnel. There is little incidence of air pollution, other than dust from vehicles and smoke from occasional wildfires. Noise is intermittent, and its primary sources are related to aircraft passage and scattered drilling rigs exploring for oil, natural gas, or oil shale resources. The natural landscape of the area is in some places interspersed by roads and trails, cleared fence lines and gas pipelines on cleared rights-of-way.

Assuming surface-mine development, the tract would lose its natural quiet at the mine and plant site. Noises associated with the activities of the operation will be greatest at the mine and plant sites and at spent shale disposal areas.

Air quality would be slightly degraded due to the dust from oil shale operations and vehicles associated with such operations. Impact from the mine and retort may not be noticeable in the immediate area during the summer months since meteorological lifting will disperse particles in prevailing winds aloft. However, inversions during the winter months occasionally may trap and concentrate emissions over the Piceance Basin and could result in accumulation of particulate contaminants in the atmosphere.

The visual impact from the disposal of spent shale and over-burden storage would be noticeable until restoration activities are completed. A plant would be visible from ridge tops kilometers away. Spent shale disposal in some cases would alter the view of scenic areas from atop bluffs. However, the development of a large surface mine would provide an unusual attraction which could increase tourist traffic. Some visual impact on the asymmetric landscape would result from utility rights-of-way such as pipelines, powerlines, roads, and stacks and plumes. During the first 5 years, surface mine development would eliminate some of the existing recreation areas. After vegetation has been successfully reestablished on a site, the area would be able to sustain levels of recreation that may be similar to those previously existing.

With underground mining, recreation opportunities lost would be small during the first 5 years; with 30 and 50 percent in 20 and 30 years, respectively, assuming no rehabilitation, and 15 and 20 percent with rehabilitation.

With in-situ mining, the recreational area lost would be approximately 20 percent after 10 years operation.

Deer hunters will be displaced from the same areas to other areas in the Piceance Creek Basin and/or adjacent regions. These hunters, as well as those related to normal population growth, will increase hunter density in the adjacent areas, thus lowering the existing quality of the hunting experience.

Outdoor recreational benefits which may be gained because of improved accessibility include sightseeing, both on and off the road camping, and fishing throughout the basin and on adjacent private and public lands. In addition, the oil shale project may increase visitor use of the basin as a tourist attraction beyond that of normal outdoor recreation activities.

Pipelines, power lines, roads and other service facilities would change the existing landscape. Noise created by crushing and retorting operations and the movement of heavy equipment in disposing of spent shales would impact the aesthetic value of the area, as would the minor petroleum odors from the retorted hydrocarbon liquids and gases.

Economic and Social Development

Population

The 1970 population of the tri-state oil shale area was about 120,000 persons and is at present probably the same. For each 50,000 barrel per day of oil shale the population is expected to increase by 8,600 persons during the 3 year construction period and thereafter by 6,200 persons as a permanent increase. An additional permanent increase in population of about 600 persons would result from the influx of persons in business fields and service industries to accommodate the increased population employed by the oil shape industry, making a total permanent increase of 6,800 persons in the area population for each 50,000 barrel per day operation. With the probability of several such operations it is evident that a tremendous population increase could in 5 to 10 years result for the area under consideration.

Tax Revenue

In the tri-state area in recent years tax revenue has varied, according to location and at different times from $112 to $325 per capita. It is expected that with the start and with the significant expansion of an oil shale industry this revenue would increase considerably to a level of around $1,000 per capita.

Personal Income

No estimates are available concerning the average per capita income in the area, but it would probably increase several orders of magnitude over present levels.

Commuting Patterns

Commuting patterns would change drastically from present patterns for evident reasons, and the changes would result in not only the improvement of present roads and highways, but the construction of many miles of new ones.

Building Industry

There would be a "boom" in the building industry because of the need for industrial, business, and residential construction to serve the new oil shale industry of the area. Whole new towns probably would be created.

Zoning and Planning

Good zoning and building codes will be necessary to insure the quality of industrial and urban development.

Nonagricultural employment is at present evenly divided between white collar and blue collar jobs. Most of the oil shale plant jobs will be blue collar jobs, but the new urban support jobs associated with expanding communities will be white collar and service. The overall composition of employment will shift to a larger percentage of blue collar jobs. These shifts in the composition of urban populations could cause strains to develop between the established residents and the newcomers. A mutual effort will be needed to mitigate these strains if they occur.

Demand for Public Utilities, Police, and Fire Protection

Increased population and development will raise local demands for these factors in the total picture. Increased tax revenue, however, should be readily adequate to satisfy such demands.

Water Resources and Quality

Water resources of the oil shale regions of Colorado, Utah, and Wyoming are complex and varied. Surface water supplies, most of which originate from the higher elevations due to rainfall and/or snowmelt, are available from the area's large rivers - the Green, the White, and the Colorado. Groundwater is also a potential source of water for oil shale development, particularly within the Piceance Creek Basin of Colorado.

Demand for water will be created for use in processing as well as for use in communities that will be required to support industrial development. The water required for processing and for associated urban populations has been the subject of several investigations. These studies have provided important background information concerning the general range of water requirements including water requirements not only for mining and crushing, but also for shale disposal and revegetation and for cooling water for process and domestic power.

Water consumed in processing and that consumed for an associated urban population are listed separately in Table 16 for various 50,000 bbl/day extraction methods. This table was based on the sources discussed below.

TABLE 16. WATER CONSUMED BY OPTIONAL MINING METHODS FOR SHALE OIL PRODUCTION(5)
(Acre-feet/year)

	Shale Oil Production	(Barrels per day)	
	50,000 Underground	50,000 Surface Mine	50,000 In Situ
PROCESS REQUIREMENTS			
Mining and Crushing	370-510	365-510	-
Retorting	580-730	585-730	-
Shale Oil Upgrading	1,460-2,190	1,460-2,190	1,460-2,220
Processed Shale Disposal	2,900-4,400(a)	2,920-4,375	-
Power Requirements	730-1020	730-1,020	730-1,820
Revegetation	0-700	0-350	0-700
Sanitary Use	20-50	15-35	20-40
Subtotal	6,060-9000	6,075-9,210	2,210-4,780
ASSOCIATED URBAN			
Domestic Use	670-910	570-765	720-840
Domestic Power	70-90	55-75	70-80
Subtotal	740-1,000	625-840	790-920
GRAND TOTAL	6,800-10,600	6,700-10,050	3,000-5,700
AVERAGE VALUE	8,700	8,400	4,400

(a) Water used is 20% by weight of the disposed spent shale.

Water requirements for mining, crushing, retorting, and shale-oil upgrading are based on process engineering studies by the U.S. Bureau of Mines; water power requirements are based on Jimeson and Adkins.(5) The water needs for shale disposal are based on stability research by Denver Research Institute, on experimental work by Colorado State University, and by the Colony Development Operation. Water requirements for revegetation of processed or spent shale will range from zero as a given area is built up, to about 1 foot per year for each acre to be revegetated. Urban population water requirements associated with a given plant size were made by the U.S. Bureau of Mines, and the water demands per capita have been obtained from the work of Ryan and Wells.(5)

A block diagram depicting the demand and supply of water for two regions are presented in Figures 13 and 14 for different tracts* in the Green River basin. Each of these diagrams is based on a 50,000 bbl/day plant for an underground mine, ex-situ plant. The diagram of Figure 14 shows that significant amounts of mine water to meet the demands for low quality water at the plant are available. It is suggested that it may be possible to operate the plant with a low withdrawal rate from the mine so that problems of its disposal are minimized. If mining operations require a higher withdrawal rate than plant water demands, the excess water will have to be released to either the natural creek or the river after treatment. This is another area that requires considerable study.

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* The tracts U-a and U-b, and C-b are as referenced in Volume III of Reference (5).

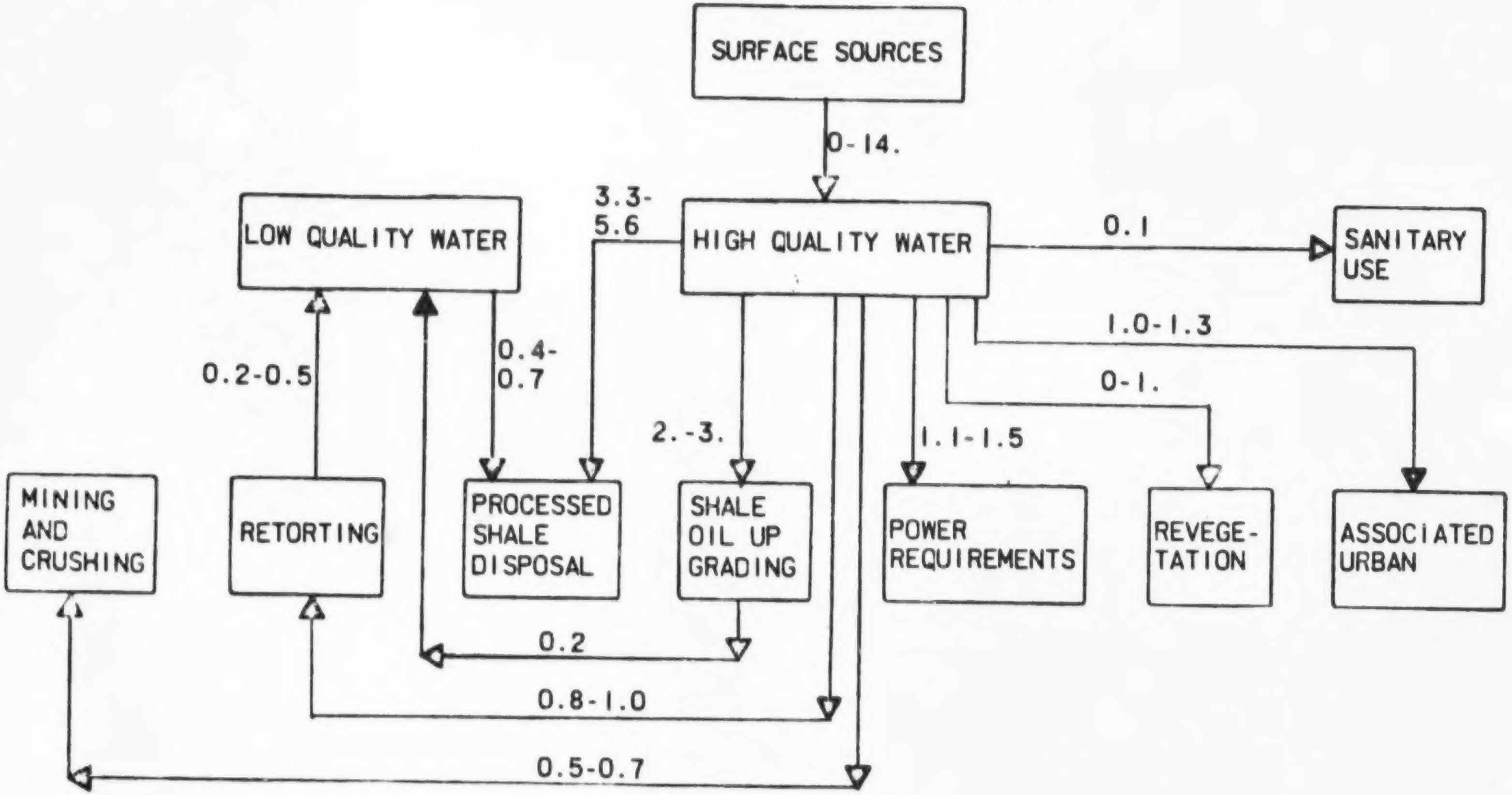
SURFACE SOURCES
0-14.
HIGH QUALITY WATER
0.1
SANITARY USE
1.0-1.3
0-1.
1.1-1.5
3.3-5.6
2.-3.
LOW QUALITY WATER
0.4-0.7
0.2-0.5
MINING AND CRUSHING
RETORTING
PROCESSED SHALE DISPOSAL
SHALE OIL UP GRADING
POWER REQUIREMENTS
REVEGE-TATION
ASSOCIATED URBAN
0.2
0.8-1.0
0.5-0.7

FIGURE 13. DEMAND AND SUPPLY FOR WATER :
50,000 Barrel Per Day Underground Mine,
Tracts U-a and U-b (cu.ft. per sec)

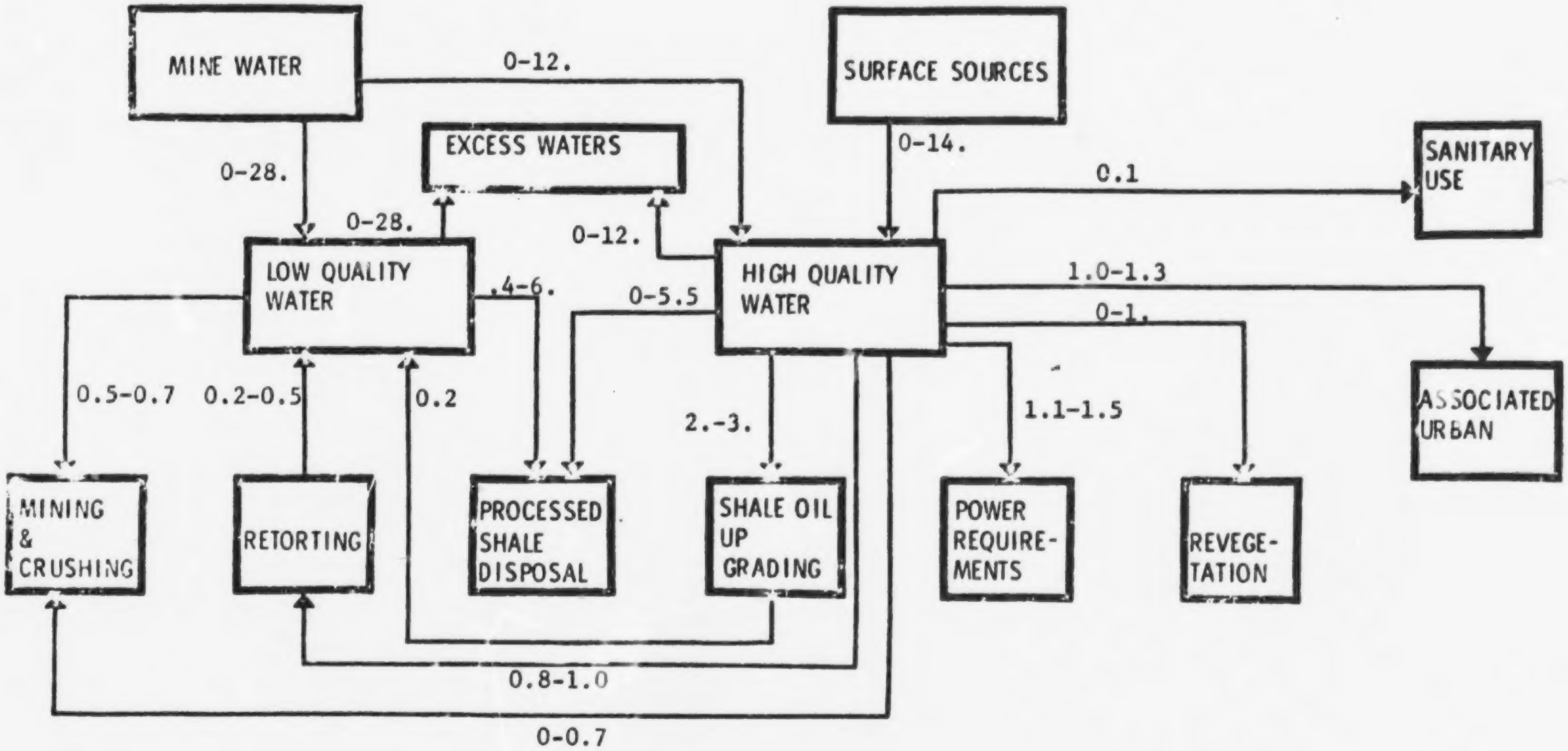
MINE WATER
SURFACE SOURCES
EXCESS WATERS
SANITARY USE
LOW QUALITY WATER
HIGH QUALITY WATER
ASSOCIATED URBAN
MINING & CRUSHING
RETORTING
PROCESSED SHALE DISPOSAL
SHALE OIL UP GRADING
POWER REQUIREMENTS
REVEGETATION
0-12.
0-28.
0-14.
0.1
0-28.
0-12.
.4-6.
0-5.5
1.0-1.3
0-1.
0.5-0.7
0.2-0.5
0.2
2.-3.
1.1-1.5
0.8-1.0
0-0.7

FIGURE 14. DEMAND AND SUPPLY FOR WATER: 50,000 Barrel Per Day Underground Mine, Tract C-b (cu. ft. per sec.) (Assumes 40 cfs pumped initially, of which 12 cfs is of high quality water and 28 cfs is of low quality water)

VIII. PRODUCT TREATMENT AND USAGE

The usage of the products and by-products from the oil shale industry is reviewed in this chapter. The review covers product composition as a function of retorting method, required treatment prior to use, and the economic and environmental impact and energy capability resulting from the use of these new products.

Gaseous Products

Gas Composition as a Function of Retorting Method

Different retort gas compositions will result from different retorting methods. The compositions of the retort gases and the reasons for their differences, discussed in detail in the section on retorting, will be briefly reviewed here.

Shale oil is heated to the vapor state, drawn out of the retort and thereby separated from the oil shale. In the process a certain quantity of retort gas is also produced from the cracking of the hydrocarbons. The quantity and quality of this retort gas depend to a large extent on the method and temperature of heating. Basically, there are three retorting schemes, 1) internal combustion retorting, 2) indirect heat retorting and 3) in-situ retorting. These schemes are summarized below.

1) Retorting by Internal Combustion Heating: crushed shale is feed to a vertical kiln wherein a major portion of the shale oil is liberated by pyrolysis. The organic residue remaining on the depleted shale is ignited with the addition of combustion air and recycle gas. The gases produced, containing valuable cracked hydrocarbons, are diluted by the combustion air, carbon dioxide, and by the products of the thermal decomposition of inorganic carbonates.

2) Retorting by Indirect Heating: crushed shale is fed to a vertical kiln or horizontal rotary kiln wherein a major portion of the shale oil is liberated from the oil shale by pyrolysis. Heat is supplied not by internal combustion but by introduction of some heat transferring medium such as heated retort gas or heated ceramic balls. The gases produced therefore contain primarily cracked hydrocarbons and very little inerts. In addition, since indirect heating can often be carried out at lower temperatures the extent of carbonate decomposition and hence dilution of the retort gas by CO_2 is reduced or avoided completely.
3) Retorting by In-Situ Combustion Heating: unmined oil shale in the formation (or in-situ) is artificially fractured to induce mass permeability. The formation is then ignited to generate heat and gases which liberate the oil from the oil shale by pyrolysis. Air and recycle gases are introduced through the injection well to provide (a) oxygen for the combustion process, (b) supplemental fuel for additional heating, and (c) a force to drive the combustion zone through the reservoir towards the producing wells. Because of the massive quantities of air employed the retort gas produced is severely diluted by nitrogen and oxygen.

The composition of the major constituents, heating values, and yields typical of the three retorting methods are summarized in Table 17.

Treatment Necessary Prior to Use

Because the expected uses of retort gases are retort heating and site electrical power and steam generation, treatment necessary prior to use is restricted primarily to sulfur removal. Processes employing internal combustion or in-situ retorting produce a gas diluted to a low sulfur

TABLE 17. CHARACTERISTICS AND YIELDS OF UNTREATED RETORT GASES [(5,25)]

	Type of Retorting Process				
	Internal Combustion		Indirectly Heated		In-Situ
Composition, vol. pct	(b)	(b)	As Produced	After Desulfurization	
Nitrogen[(a)]	60.1	62.1	--	--	75.5
Carbon monoxide	4.7	2.3	4.0	4.2	0.5
Carbon dioxide	29.7	24.5	23.6	24.8	15.7
Hydrogen Sulfide	0.1	0.1	4.7	(0.02)	0.1
Hydrogen	2.2	5.7	24.8	26.0	(not reported)
Hydrocarbons	3.2	5.3	42.9	45.0	1.8
Oxygen	--	--	--	--	6.8
Gross Heating Value					
kcal/scm	747	900	6975	7335	270
(Btu/scf)	(83)	(100)	(775)	(815)	(30)
Molecular Weight	32	30	25	24.7	28.7
Yield, scm/bbl oil[(c)]	582	309	25.8	24.7	
(scf/bbl oil)	(20,560)	(10,900)	(923)	(880)	(29,700)

(a) Includes oxygen of less than 1.0 volume percent.

(b) First analysis reflects relatively high-temperature retorting in comparison with second, promoting higher yield of carbon oxides from shale carbonate and relatively high yield of total gas.

(c) Oil from the retort, or shale formation.

concentration which makes prior treatment for desulfurization economically unattractive. Such processes most likely will require stack gas scrubbing to meet air quality standards.

Processes employing indirectly heated retorts have the advantage that they produce an undiluted, relatively high sulfur-concentration gas amenable to economical gas desulfurization techniques. The actual process steps, the same as those employed for gases produced in the crude shale oil upgrading processes, will be described in detail in a following section outlining the shale oil upgrading procedures.

Economic Impact of Gaseous Products

Gaseous products produced either by retorting or on-site upgrading of the crude shale oil are expected to be consumed at either the retorting or upgrading facilities or for the generation of on-site electrical power and steam requirements. Even if a high Btu gas could be produced in quantities large enough to exceed on-site requirements, the volume available for export would not be significant in comparison to other sources of gaseous fuels.

Environmental Impact of Gaseous Products

The environmental impact of product gas usage, since the vast majority will be consumed on-site, will be a local problem involved mainly in combustion processes. Technology is currently available for adequate particulate control. However, control of sulfur and nitrogen oxides have not reached such an advanced stage. Combustion, without control of these emissions, could have a significant effect with a developed industry (300,000-400,000 bbl/day operations) because of the relative purity of the present oil shale lands' environment. Enforcement of current particulate and sulfur control regulations should reduce adverse effects to an acceptable level. However, with the promulgation of new regulations or enforcement of "nondegradation" standards, these emissions would have to be reduced even further.

Energy Capability of Gaseous Products

The vast majority of gaseous products will be consumed on-site as fuel; therefore, the energy capability of these products available for export will be very small and totally negligible on a national scale.

Crude Shale Oil Products and By-Products

Shale Oil Composition as a Function of Retorting Method

Crude shale oil from Green River oil shale varies slightly in its characteristics, depending on the above ground retorting method used. The geographic area and the geologic age of a particular oil shale zone appears to have only a minor influence on the properties of the oil. Information on the crude oil produced from in-situ retorting is more limited; however, as noted in Table 18 it has a much lower pour point and viscosity -- low enough to permit pipelining without further processing. Another difference, not noted in the table, is that in-situ oil is more highly saturated and contains more than twice the naphtha and light distillate content of oil produced by above-ground retorting. These characteristics indicate that, with exception of degree of saturation, in-situ crude shale oil is similar to the coker distillates from other crude oils and suggests that similar refining techniques should be appropriate.(27)

Table 19 displays typical properties of crude shale oil produced by above ground retorting and syncrude (crude shale oil upgraded by a catalytic hydrogenation process). Similar data for in-situ crude oil are not available. Over 50 volume percent of the in-situ oils boil below 316 C (600 F), compared with approximately 30 percent of most ex-situ shale oils. The fraction of the in-situ oil having a boiling range from 425-535 C (800 to 1000 F) ranged from 12 to 18 percent, compared with 27 to 57 percent characteristic oils from above ground retorts.(25) This in effect states the production of lower boiling distillates will be greater from in-situ crude and the production of coke will be greater from shale oil extracted by ex-situ methods.

TABLE 18. CHARACTERISTICS OF CRUDE SHALE OILS[13,27]

	Retorting Process			
	Gas Combustion	Union[a]	TOSCO[b]	In Situ[c]
Gravity, API	19.7	20.7	28.0	36.2
Sulfur, wt %	0.74	0.77	0.80	0.79
Nitrogen, wt %	2.18	2.01	1.70	1.14
Pour Point, C (F)	28 (80)	32 (90)	23 (75)	-13 (9)
Viscosity, centistoke @ 38 C (SUS @ 100 F)	55.3 (256)	48 (223)	25.4 (120)	5.2 (43)

(a) Typical of product from original Union process.

(b) Unpublished information submitted by Colony Development Operation indicates TOSCO crude shale oil may have gravity as low as 21 API and sulfur content of 0.75 wt %.

(c) Average of values presented in Table 2.

TABLE 19. TYPICAL PROPERTIES OF CRUDE SHALE OIL AND SYNCRUDE (1)

	Crude Shale Oil	Syncrude
Gravity, API	28.0	46.2
Pour Point, C	24	10
(F)	(75)	(50)
Sulfur, wt %	0.8	0.005
Nitrogen, wt %	1.7	0.035
Reid Vapor Pressure, atm	-	1.5
(psi)	-	(8)
Viscosity, centistoke @ 38 C	25.4	4.3
(SUS @ 100 F)	(120)	(40)
Analysis of Fractions		
Butanes and Butenes, vol %		
C_5-177 C (350 F) Naphtha		
Vol %	19.1	27.5
Gravity, °API	50.0	54.5
Sulfur, wt %	0.70	<0.0001
Nitrogen, wt %	0.75	0.0001
K Factor	11.7	12.0
Aromatics, vol %	-	18
Naphthenes, vol %	-	37
Paraffins, vol %	-	45
177-288 C (350-550 F) Distillate		
Vol %	17.3	41.0
Gravity, °API	31.0	38.3
Sulfur, wt %	0.80	0.0008
Nitrogen, wt %	1.35	0.0075
Aromatics, vol %	-	34
Freezing Point, C (F)	-	-37 (-35)
288-455 C (555-850 F) Distillate		
Vol %	33.0	22.5
Gravity, °API	21.0	33.1
Sulfur, wt %	0.80	<0.01
Nitrogen, wt %	1.90	0.12
Pour Point, C (F)	-	27 (80)
455 C (850 F) - Plus Residue		
Vol %	26.0	None
Gravity, °API	12.0	
Sulfur, wt %	1.0	
Nitrogen, wt %	2.4	

Necessary Treatment Prior to Use

Crude shale oil produced by both ex-situ and in-situ retorting is a black, viscous, foul-smelling, high nitrogen, relatively high sulfur oil that is usually a slushy solid at room temperature. It tends to form sludge and otherwise deteriorate if stored for prolonged periods of time. Direct combustion of this material as fuel is not considered likely. Instead, on-site upgrading to convert the crude shale oil to pipeline quality, followed by processing at a petroleum refinery is considered the most likely scheme for recovery of fuel and chemical products.

Shale oil has several qualities which make it a superior refinery feedstock. There is essentially no fuel-oil cut in the shale oil which means a higher yield of gasoline and middle distillates, shale oil has a lower sulfur and nitrogen content, after upgrading, than most crudes, and it has a lower aromatic content. Shale oil does, however, have a higher percentage of unstable molecules that have a tendency to react to form gums and other undesirable compounds. Although it has some unusual characteristics, it is similar in most respects to conventional crude oil and can be accepted for processing by conventional techniques to manufacture high-quality petroleum products including gasoline, jet and diesel fuels, and domestic and industrial heating oils.

Crude shale oil from in-situ retorting, as noted earlier, has certain physical and chemical properties different from shale oil produced by above ground retorting. These differences will allow direct pumping to refineries for processing with no prior upgrading. It appears unlikely that a large refining industry will develop in the area of the oil shale deposits. The market for products in this area is small and it is preferable, for economic reasons, to transport crude oil out of the area rather than finished products. An additional and perhaps even more compelling motivation for avoiding refining near the oil shale retorting area is the limited water resources.

It can be expected however, that early oil shale plants will include facilities for upgrading shale oil. Upgrading is necessary because shale oil has a high pour point and viscosity which need to be reduced to facilitate handling in pipelines. In addition, upgrading is necessary to remove the unusually high concentration of nitrogen compounds which would otherwise deactivate catalysts used in petroleum refining processes such as catalytic cracking, hydrocracking and reforming.

Thus, the necessary treatment prior to use of the crude shale oil can be divided into two stages: (1) on-site upgrading of crude shale to pipeline quality through processing for the removal of nitrogen and sulfur, and (2) refining the syncrude (crude shale oil subjected to catalytic hydrogenation) to fuel products and chemicals.

On-Site Upgrading--Coking and Hydrotreating of Distillate. There are a number of possible processing sequences and proprietary processes suitable for removing nitrogen from shale oil. One set of alternatives that is applicable to a typical crude shale oil is illustrated in Figure 15. In this scheme the crude shale oil is heated to vaporize a portion of the oil and the resulting mixture of liquid and vapor is fed to a distillation column in which light oil, naphtha and gas are removed from the upper section of the column and heavy oil and resid are removed from the bottom section.

The resid is further heated and processed in a delayed coking unit wherein a thermal cracking process with chemical reactions similar to those in retorting takes place. The products from coking are petroleum coke and a vapor stream containing gas, naphtha, light oil and heavy oil. This vapor stream flows back to the crude distillation and gas processing units for separation of the various constituents. The products of the gas processing section are specifically: high quality fuel gas, light naphtha and by-product hydrogen sulfide from which sulfur can be obtained. The products of distillation are naphtha and light and heavy distillates.

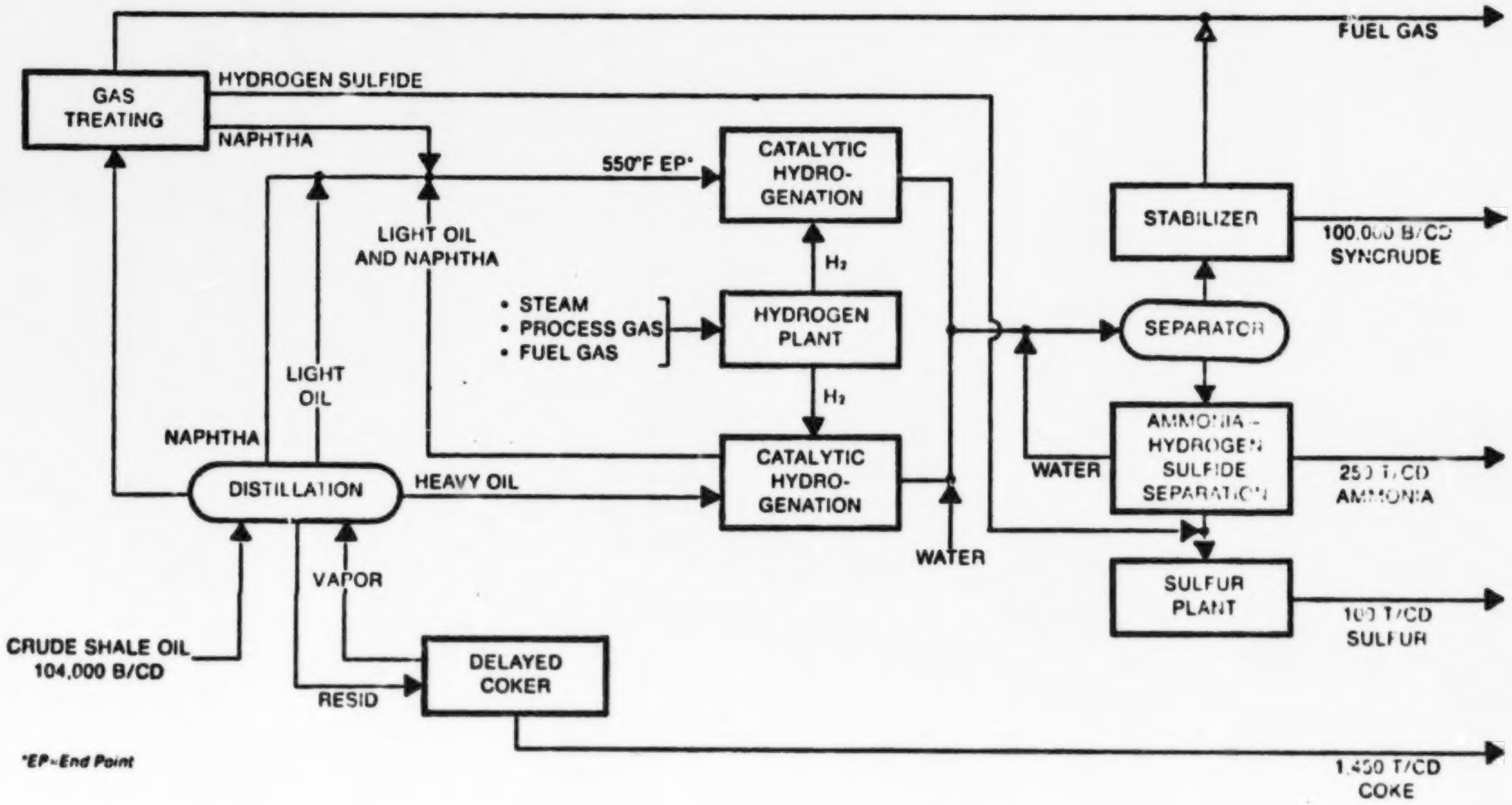
GAS TREATING
HYDROGEN SULFIDE
NAPHTHA
550°F EP*
CATALYTIC HYDRO-GENATION
LIGHT OIL AND NAPHTHA
• STEAM
• PROCESS GAS
• FUEL GAS
H₂
HYDROGEN PLANT
H₂
LIGHT OIL
NAPHTHA
DISTILLATION
HEAVY OIL
CATALYTIC HYDRO-GENATION
VAPOR
CRUDE SHALE OIL 104,000 B/CD
RESID
DELAYED COKER
WATER
WATER
STABILIZER
SEPARATOR
AMMONIA - HYDROGEN SULFIDE SEPARATION
SULFUR PLANT
FUEL GAS
100,000 B/CD SYNCRUDE
250 T/CD AMMONIA
100 T/CD SULFUR
1,450 T/CD COKE
*EP–End Point

FIGURE 15. FLOW DIAGRAM FOR UPGRADING CRUDE SHALE OIL(1)

The naphtha, light oil and heavy oil from the retorting and coking steps are hydrogenated to remove nitrogen. The hydrogenation process comprises heating the oil feed to an elevated temperature i.e., 316-455 C and treating with a catalyst in the presence of hydrogen at elevated pressure i.e., 41.8-205.2 atm (600 to 3000 psi). The reaction produces sulfur-free, low nitrogen-content hydrogenated oils, ammonia, hydrogen sulfide and a small amount of gas. The hydrogenated oils are then blended with butanes, pentanes and hexanes from gas and naphtha treating to produce the finished syncrude.

The products from the hydrogenation unit are mixed with water to remove ammonia and hydrogen sulfide. This water stream is then separated by gravity from the oil and gas products and is distilled to separate hydrogen sulfide and ammonia from each other and from the water. The water is recycled. The ammonia, produced at a rate of approximately 2.3 kg/bbl (5 lb/bbl), is liquified for storage and sale. Hydrogen sulfide is converted by the conventional Claus Process to elemental sulfur (0.9 kg/bbl) and can be sold as such. The small amount of gas formed in the catalytic hydrogenation process is separated from the hydrotreated synthetic crude by distillation and can be used for plant fuel or for hydrogen plant feed. Hydrogen required in the catalytic hydrogenation process is manufactured by reforming of natural gas or other light hydrocarbons by catalytic, high-temperature reaction with steam.(1,5)

There are a number of variations which can be applied to the processing sequence shown in Figure 15 including: (a) addition of a second-stage vacuum distillation for the feed to cause more of the crude shale oil to flow directly to hydrogenation and, if carried far enough, eliminating delayed coking, (b) replacement of the delayed coking unit with a catalytic hydrotreating system designed for heavy oil, (c) combining hydrogenation units for the naphtha and gas oils, and (d) generation of hydrogen by partial oxidation of oil rather than reforming of light hydrocarbons. However, the scheme shown has been researched a great deal and is relatively simple.

Refining Syncrude. The refinery operations to convert syncrude to marketable petroleum products has received less attention than the required on-site upgrading processes because it believed that currently employed refining techniques can easily be adapted to process syncrude. Commercial processing of shale oil was performed on a limited basis (20,000 bbl) at American Gilsonite Company's Grand Junction, Colorado, refinery in 1961 using shale oil produced in the Union Oil retort.(20) Regular and premium gasoline were among the products produced by a three step upgrading-refining scheme. These steps were: (1) upgrading by coking, (2) upgrading by hydrogenation, and (3) refining by hydrocracking or catcracking and reforming. More recent investigations were conducted by Phillips Petroleum Company. Researchers postulated that the most economic sequence of refining steps, displayed in Figure 16, would be recycle coking and hydrostabilization in one or more passes and fractionation. Distillates requiring further nitrogen reduction (to avoid catalyst poisoning) would be separately processed. Naphtha would be reformed to increase octane number by dehydrogenation of naphthenes to aromatics and isomerization of paraffins. Heavier distillates would be catalytically cracked to products of lower boiling ranges. It was concluded from this work that the refining processes used--coking and hydrostabilization (upgrading), hydro-denitrification, reforming and cracking -- converted raw shale oil into petroleum products suitable for sale in present markets, and the processes were capable of sustained operation. Optimization is considered likely upon further study of the process variables.

Economic Impact of Shale Oil Products

The products derivable from shale oil by upgrading and refining operations are listed in Table 20. Products from shale oil are expected to enter the fuels and chemicals market as a supplement to domestic production. The fully developed oil shale industry is envisioned to be limited to approximately 5 million bbl/day because of water scarcity and other restricting conditions discussed throughout this report. At this rate gasoline, jet, and diesel fuel from oil shale will not supplant domestic oil production. Regardless, both the refined oil and by-products from processing the crude shale oil and syncrude will have a significant impact on the domestic economy.

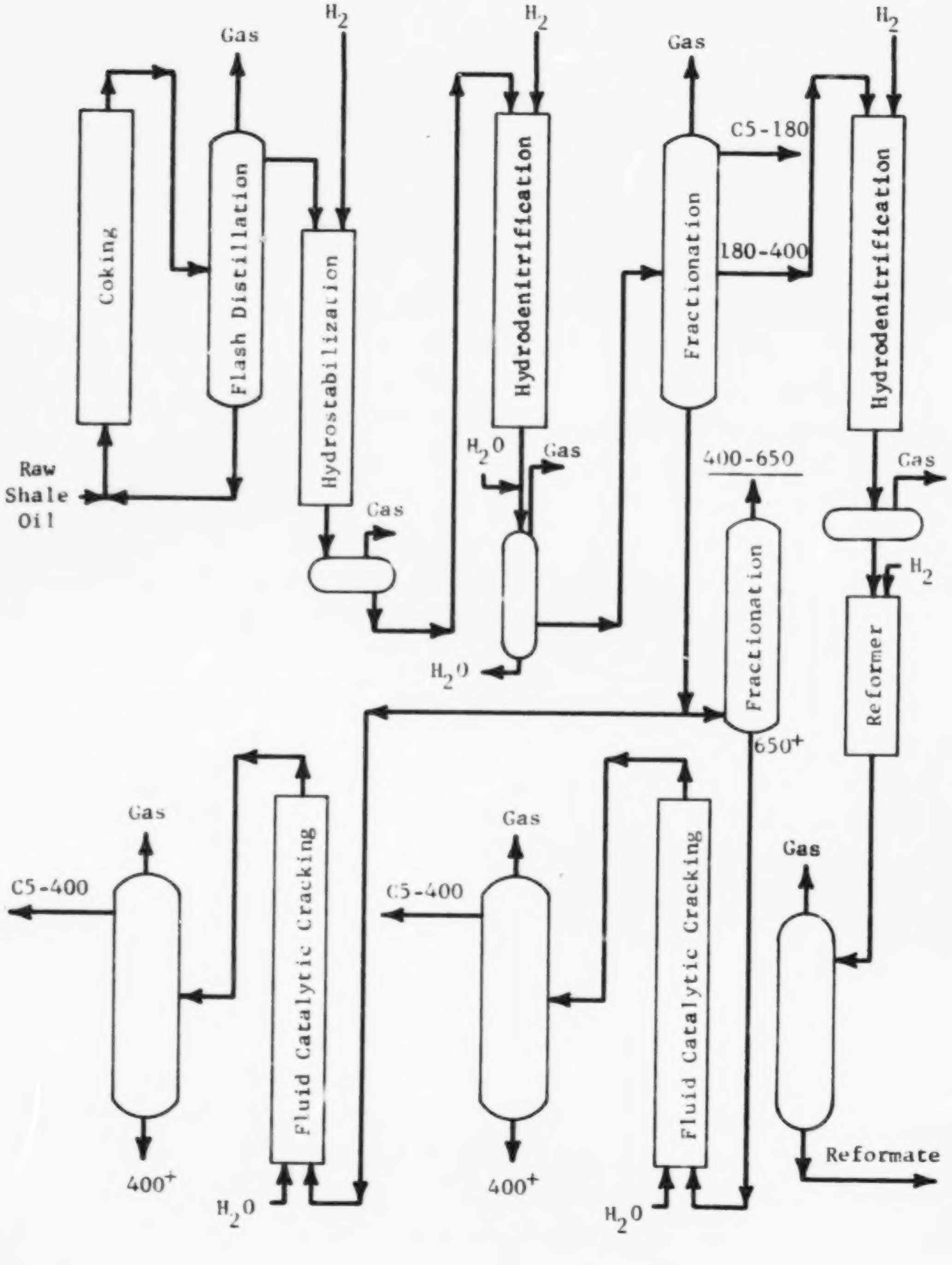
Gas
H2
H2
Gas
H2
C5-180
Coking
Flash Distillation
Hydrostabilization
Hydrodenitrification
Fractionation
180-400
Hydrodenitrification
Raw
Shale
Oil
H2O
Gas
400-650
Gas
Gas
H2
Gas
Fractionation
Reformer
H2O
650+
Gas
Gas
Gas
C5-400
C5-400
Fluid Catalytic Cracking
Fluid Catalytic Cracking
400+
400+
Reformate
H2O
H2O

FIGURE 16. REFINING OF SHALE OIL(28)

TABLE 20. PRODUCTS FROM SHALE OIL PROCESSING (1,2,5,29)

Processing	Product
Upgrading	Ammonia Sulfur Green Coke Syncrude Gas
Refining	Gasoline Jet and diesel fuels Domestic and industrial heating oil Solvents Paraffin wax Asphalt Petrochemical plant feed stock Tar acids Tar bases

By-products obtained from the upgrading of crude shale oil -- sulfur, ammonia, green coke, and fuel gas -- could add new supplies to the economy. Production at the 1 million bbl/day level could provide upwards of 4 percent of the U.S. sulfur demand and 7 percent of ammonia demand (based on 1968 figures). The green coke and fuel gas produced are expected to supply nearly all the on-site energy needs. The coke may be utilized as a more valuable raw material in metallurgical uses or for manufacture of electrodes. By-products from shale oil refining are expected to be typical of the petroleum industry. The major by-products, noted previously , will probably be solvents, paraffin wax, asphalt, and petrochemical feedstocks (such as ethylene, propylene, butylene, benzene and naphtha). Some of the major petrochemical products derived from these raw materials are organic chemicals, synthetic rubber, plastics, carbon black, and synthetic fibers. Some by-products not commonly obtained from petroleum refining may be produced by shale oil refineries. Among these are tar acids and tar bases which can be refined to phenol and pyridine base compounds, respectively. These shale oil by-products can be expected to have an appreciable impact on the chemical and petrochemical industries--resulting in shale oil refineries operation modified specifically to market demand for by-products as well as the main products.

Environmental Impact of Shale Oil Products

The impact of both the main products and by-products from shale oil processing on the environment is restricted to that resulting from the product's usage. Fuels produced from upgraded crude shale oil will be low in sulfur and nitrogen. Therefore, combustion of these products should result in low sulfur and nitrogen oxide emissions. However, since the liquid fuels produced from shale oil will be mainly gasoline and jet and diesel fuels (fuels typically low in sulfur and nitrogen compounds), the overall increase in emissions from combustion should be similar to that anticipated from increased petroleum based fuel usage rather than because of differences in properties of gasoline, jet fuel, and diesel fuel produced from oil shale.

By-products will provide new sources of currently employed chemicals, not new products. Therefore, utilization of these chemicals, produced in new low pollution facilities, will either reduce emissions by supplanting existing (and likely more polluting) processes for the production of these chemicals, or provide a low pollution source of additional supplies required by increasing demand.

Energy Capability of Shale Oil Products

A well-developed shale oil industry will be capable of increasing the domestic supplies of crude oil. The energy capability of these products will depend on the extent of development of the industry as well as the yield of fuels from the crude shale oil. A reasonable production schedule, provided favorable economic, environmental, and technical influences prevail, is displayed in Table 21.

TABLE 21. PROJECTED SHALE OIL PRODUCTION

	Thousand bbl/calendar day	10^{12} kcal/year	10^{12} Btu/year
1978 through mid-year 1981	100	49.6	197
Mid-year 1981 through 1983	200	99.3	394
1984-1985	400	198.6	788

A maximum production capacity of approximately 5 MM bbl/day is predicted (assuming all other factors favorable) because of water availability limitations. The production rate of 400,000 bbl/day will have a nearly insignificant effect on the total U. S. energy supply and demand in 1985, reducing the quantity of imported oil by only 0.7 percent. By assuming the continuing growth pattern in both import oil requirements (0.8 MM bbl/day increase per year) and the oil shale industry growth (0.1 MM bbl/day increase per year), and that domestic oil production will remain approximately constant, by the year 2000 oil shale potentially could reduce foreign oil imports by 7 percent. However, the crude produced by oil shale developments, expressed differently, would provide an increase of 15 percent in domestic oil supply. Therefore, shale oil should provide a significant long-term energy supply of liquid energy sources.

Other By-Products

The possibility of producing alumina and soda ash in addition to shale oil was noted earlier.

Another possible product from spent oil shale is portland cement clinker, a major product of the Estonion (USSR) oil shale industry. The shale has been shown to offer high strength and high resistance to frost following extended heat treatment.

Economic Impact of Other By-Products

The development of large scale facilities for the production of alumina, nahcolite, and soda ash connected with the oil shale industry could have a significant effect on the domestic economy. The most important product would naturally be alumina, employed primarily for aluminum and abrasives, chemicals production, and refractory production. Presently the United States is heavily dependent on foreign sources for about 90 percent of its alumina ore. Development of the vast resources available in the oil shale regions could provide alumina (and therefore aluminum) self-sufficiency. Estimates on the quantity of alumina obtainable depend on the dawsonite content of the shale; however, it is estimated that a 100,000 bbl/day facility would produce anywhere from 907 to 4080 kkg/day of alumina.(13) Alumina production from a partially developed oil shale industry of 400,000 bbl/day (estimated production capacity obtainable by 1985) would produce nearly 80 percent of domestic alumina requirements, based on 4080 kkg alumina/day production from a 100,000 bbl/day facility.

The influx of such a large new source of alumina would likely glut existing markets, with a resultant fall in bauxite and oil shale-derived alumina prices. However, it is unrealistic to expect oil shale alumina to capture a majority of the existing alumina markets immediately. Therefore, its economic impact, while still significant, will initially be somewhat limited and be gradually felt.

Soda ash from spent shale could also have appreciable economic impact. Soda ash finds applications in glass, detergent, soaps, pulp and paper, textile and water softeners, as well as in the manufacture of caustic soda, sodium phosphates, and sodium bicarbonate. Present markets, while extensive, are not expected to require the vast new quantities of soda ash obtainable from spent shale processing. Estimates of production from a single 100,000 bbl/day facility range from 7256 to 3447 kkg/day (8000 to 3800 ton/day)(38) of soda ash plus 23,320 kkg/day (25,600 ton/day) of sodium bicarbonate.(24) Coproduction of soda ash from shale on a large scale would swamp existing markets; therefore, soda ash production based on present demand is envisioned to be limited. However, while uses of nahcolite are presently limited, it shows potential as a pollution control chemical, specifically for SO_2 absorption or for acid water neutralization. Estimates of potential markets of nahcolite are very large, on the order of 550 MM kkg/yr (600 MM tons/year).

Environmental Impact of Other By-Products

The impact of other by-products from shale oil on the environment should be minimal. Alumina, the most likely major product, will be employed primarily as a raw material for the production of aluminum, and as such, would simply be displacing foreign bauxite sources. The absence of fluoride in the oil shale alumina, the major air and water pollutant from the alumina industry, could markedly reduce both air and water emissions resultant from the production of aluminum.

Soda ash and nahcolite, if produced in only limited quantities, will have little environmental impact. If employed on a larger scale, their most likely use would be in the field of pollution control chemicals; therefore, the overall environmental impact of their use would be positive.

IX. RESEARCH AND DEVELOPMENT NEEDS

The Nation's oil shale resources are of great importance to this country's future. The resources are vast* and liquid fuel which can be produced from shale is a significant source of energy. Also, some oil shales contain appreciable quantities of valuable aluminum and sodium minerals, and the cost of shale-oil production, with the rapidly rising cost of crude, is becoming more economically attractive.

Recent predictions of the rate of development of an oil shale industry range from 100,000 to 1.3 million barrels per day by 1985, but the fact remains that technology has yet to be developed and demonstrated on a commercial scale. Therefore, many new processes will have to be developed and current processes improved in the next few years in order to exploit the vast oil shale resources. The anticipated rapid development of a now infant industry provides a unique opportunity for the Federal EPA to monitor, advise, and direct the developing technology into an environmentally sound industry. The following specific research and development needs are designed for the attainment of that goal--an environmentally sound, nonpolluting or low-polluting industry.

Shale Mining

While mining research into various technical areas such as pillar design, roof stability, shaft sinking, etc., is needed, environmental related research is much more limited. Room and pillar, strip, and open pit mining have been carried out for a number of minerals throughout areas of the United States for a number of years. Specific precautions to avoid or limit emissions of pollutants to the environment have been developed. Research is needed to obtain the data required to determine the suitability of applying current mining emission control methods to the new problems encountered in oil shale mining. When and if current methods are found unacceptable, a research program should be initiated to develop new effective methods. The program should first indicate the data to be obtained, methods to be employed, and potential sources of such information. Then with the available data gathered, a determination of data gaps would be possible, and a program employing experimental mines or commercial oil-shale under ground or surface mining operations could then be investigated to obtain the missing data. Research also is needed in the area of methods and techniques of returning waste shale material to worked out mine areas for the purpose of ground stabilization and disposal and containment of spent shale.

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* Eighteen hundred billion barrels is enough to supply all U. S. oil needs for 250 years at current consumption levels if the resources can be recovered.

Ore Handling and Pretreatment

In the case of ore handling and pretreatment, there are no recommendations for research and development to be made. Equipment required is not unique and is readily available from producers of such equipment. The same is true for equipment necessary for environmental control requirements related to ore handling and pretreatment.

Retorting

The lack of experimental characterization of the effluents of the different ex-situ and in-situ retorting processes poses as one of the most significant data deficiencies which must be corrected. Recommended is an experimental test program to obtain data on the largest scale facilities practical. Such an environmental test program would determine the quantitative pollutant loads from the various emission sources, and by variation of certain process parameters the optimum process considering both process efficiency and environmental consideration could be determined. Coordinated with these emission experiments must be the determination of the applicability of conventional and new control technology for the control of emissions from the process streams employed in these studies. Solutions to those control problems encountered could then be sought through a control and treatment process development study which should include pilot plant testing of the proposed control technologies.

Additionally, another major data deficiency area is the emission levels and the applicability of current and new control technology required for the processing of the retort gas stream and for the upgrading of crude shale oil. Similar to the experimental program recommended for the retorting operations an experimental program should be initiated to investigate the control problems likely to be encountered in the retort gas processing area and in the shale oil upgrading operations. Such a program should include both an emissions testing program and pilot-plant operations for the testing of proposed control techniques.

Refuse Disposal

Specific refuse disposal research needs include large-scale experimentation for verification and optimization of methods based on preliminary conclusions obtained in small-scale disposal tests. Needs also include large-scale landfill disposal tests to determine necessary procedures for compaction, stability tests, run-off protection, percolation control, leachability, impoundment facilities, etc., with an extension of the project to include a large-scale, extended time, revegetation experiment with investigation into different varieties of plants, fertilizers, e.g., commercial versus solid waste and sewage sludge, and the method and degree of alkalinity reduction necessary. Research is needed into the refuse conveyance systems, i.e., conveyor, truck, water slurry systems, etc. The evaluation should include determination of both the environmental repercussions and economic factors such as potential mechanical problems, necessary maintenance, required capital investment, water requirements, and associated dams and water recovery methods necessary and their costs. Also to be investigated is the best configuration of disposal piles, and methods of reintroduction of spent shale into worked out mines.

The most attractive method of refuse disposal would be utilization. Therefore, research is needed into the areas of conversion of wastes into coproducts. Specific needs include investigation into the environmental and economic effects of extraction methods for alumina and sodium based minerals from raw or spent shale. Determination of the character and quantity of effluent streams should be combined with a determination of present and future markets, product purity, cost of production, transportation costs with relation to existing or future markets, and amenability of product to current or proposed processing techniques in a complete environmental-economic analysis.

Product Usage

Specific product usage research needs include examination of the environmental impact of products, by-products, and coproducts from oil shale processing when phased into the nation's economy as either a supplement to existing supplies or as the source of new products. Processing of oil shale will produce a fuel gas of differing heat content and sulfur concentration. Research is needed to examine methods of desulfurizing this gas either before or after combustion while utilizing a minimum of water. Research is also needed to investigate the environmentally acceptable modifications required by the petroleum and minerals industries to accept these new products, e.g., modification of specific petroleum refinery operations, including equipment selection, product split, catalyst usage, etc., or modification in aluminum smelting operations including the effects on water, air, and land pollution.

The overall objective of the research recommended here is to produce an authoritative document on the technology of pollution control in the oil-shale industry. Current information on environmental impacts is based on limited testing and extrapolations from related technologies. The document would be based on extensive and intensive field and laboratory research with detailed cost data for each control option. While such research may be expensive, the need for it can hardly be overlooked given the potential imminence of this emerging industry. The oil-shale industry fortunately has the option to plan for environmental controls in advance of its gearing up to meet the U. S. energy needs.

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